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DYNAMO-ELECTRIC MACHINERY:

A MANUAL FOR STUDENTS OF ELECTROTECHNICS.

BY

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FOURTH EDITION, ENLARGED AND REVISED.

FROM NEW AMERICAN TYPE SET PLATES.

L.73

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Ann Arbor
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CHAPTER XVII.

ARC-LIGHTING DYNAMOS.

For supplying arc lights, it is usual to arrange the lamps all in series, even to as many as 60 or 80 lights, and to provide a dynamo-machine which will give a constant, or nearly constant, current at a sufficiently high voltage. The usual current for which arc lamps are designed is 10 amperes. Some of the Thomson-Houston lamps are designed, however, for 6·8 amperes, and Ball arc-lamps for 4 amperes. These are therefore exceptions. On the other hand, the arc lamps used for search-lights and lighthouse work are designed to take larger currents, up to 200 amperes or more. Continuous-current voltaic arcs cannot be maintained burning steadily unless they are fed at a pressure of about 40 to 45 volts for each lamp. If the pressure is insufficient, the arcs will give out a hissing sound. The steady arc behaves as though it exercised a counter electromotive-force of about 39 volts. When arc lamps are to be used in parallel with one another, the mains must have a greater difference of potential than 45 volts—55 or 60 volts is preferable—in order that additional resistances may be introduced to steady the current through each lamp. Such additional resistances are not necessary when a number of arc lamps are used in series, as they help to steady one another. The dynamo ought, however, to be so governed as to keep the current constant, at the same strength, no matter how many or few lamps are intercalated in the circuit.

In arc-lighting in series, the function of the dynamo is to keep the amperes constant; whilst each lamp is provided with a shunt device which governs the movement of the carbons, so that the feeding of them shall keep the length of the arc, and the volts at the terminals of the lamp, approximately constant.

We may take it, therefore, that a system of 20 arcs in series will require a dynamo giving a current of, say, 10 amperes, and a pressure, when all the lamps are in use, of nearly 1000 volts. This allows 45 volts per lamp, and 5 volts more for the resistance of the wires between each lamp and the next.

Constant current dynamos are also needed for the purposes of municipal lighting by means of special glow-lamps, with thick carbon wires instead of thin filaments connected in series, so that the same current flows successively through a large number of them.

It was suggested by Deprez in 1881, that by a species of compound winding, consisting of an initial excitation and a shunt excitation combined, a dynamo might be constructed to give a constant current at constant speed. The assumption which underlay his reasoning, that the magnetism is proportional to the exciting power, is, we know, not justified except for the early and unstable stage of magnetization; and all attempts to produce a practical compound winding for this purpose have failed.

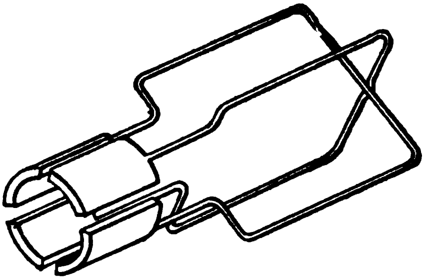
Owing to the circumstance (p. 110) that the torque of a dynamo is proportional to the current, it is found that when a dynamo with well-excited field-magnets is driven from its own engine, with constant steam-pressure, but not governed to run at a fixed speed, it will of itself run very nearly at such speeds as shall keep the current constant. But as this mode of governing is inadmissible in those cases where the engine has to drive at a constant speed, other modes of keeping the current constant are resorted to, which are discussed in Chapter XXVII. on Regulators.

For the production of constant currents at such high voltages as 2000 to 3000 volts the ordinary ring and drum armatures, wound in a closed coil, in numerous sections, and provided with a commutator consisting of numerous closely-packed parallel bars, have not been found entirely satisfactory, for the commutator of this type is liable to give way under the high pressure, and to deteriorate under the action of long sparks flashing over its surface from brush to brush under the wide alterations of lead that are inseparable with this mode of working. In Deprez's experiments on transmission of power to a distance by currents at very high pressure, machines with Gramme armatures wound with very fine wire were used, giving from 4000 to 6000 volts. They gave incessant trouble from the breaking down of the resistance. Nevertheless, good results have been obtained more recently by Messrs. Paterson and Cooper, and also by Lahmeyer of Frankfort, in the use of high voltages in machines having ordinary commutators with many segments. Experience, however, is in the main against the use of armatures of this type. More simple forms are needed that will not break down under the conditions of work. These forms are usually associated with other modes of construction in which the armature winding does not constitute a closed coil.

OPEN-COIL DYNAMOS.

As explained on p. 40, it is possible to construct armatures in which the separate coils or sections of the windings are not united together into one closed circuit. An example is given in Fig. 290. This diagram (which should be compared with Fig. 24, p. 37) shows an armature consisting of two

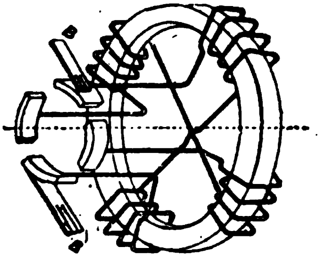
FIG. 290.



SIMPLE OPEN-COIL ARMATURE.

separate loops, set in planes at right angles to one another, so that when one is passing through the inactive region the other is in the position of maximum action. There is no reason why these two loops should not have each a separate 2-part commutator like that of Fig. 24; and one pair of brushes might press on both commutators. It is, however, obviously more convenient to unite these two commutators into a single one of four parts, as in Fig. 290; and then it will at once be seen that as this rotates between its pair of brushes one loop only will be in action at once, the other loop being cut out of circuit for the time being. It would clearly be possible to arrange any number of loops or coils in this way so that only that loop or coil which was passing through the position of maximum action should be feeding the brushes, all the rest being meantime open-circuited. A ring armature wound in sections might of course be similarly arranged, so that the pairs of sections had each a separate commutator; and Fig. 291 (which should be compared with Fig. 31, p. 39) shows such a ring, but with the two commutators cut down and formed into a 4-part collector.

FIG. 291.

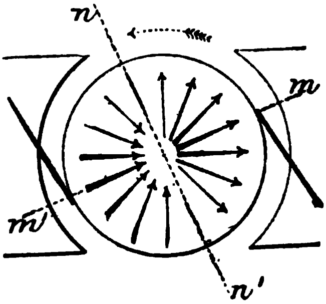


FOUR-PART OPEN-COIL RING ARMATURE.

It will be noticed that each coil is joined at the back to the one diametrically opposite to it, and that the front ends of the coils pass to the commutator. As a matter of fact, it would make no difference in either of these armatures were the wires which cross at the back all united where they meet. In order further to follow the action we will refer to Fig. 292.

This diagram represents by means of radial arrows the electromotive-forces induced in a loop or loops rotating (*left-handedly*, as it happens, in this figure) in a magnetic field (with N-pole on the left in this case). The action is a maximum along the line of the resultant magnetic field *m m′* (which would be horizontal were it not for the reactions explained in Chapter IV.), and is a minimum along the line *n n′*. The reader will remember that line *n n′* is the neutral line which lies nearly at right angles to the line of maximum magnetization; and that, for those armatures in which all the coils are joined together in a closed circuit, it is at *n n′* that the brushes have to be placed. But when each coil is independent of the others it is no use putting the brushes at *n n′*; they must be put at *m m′*; the line of maximum action coinciding in this case with the diameter of commutation. But those coils which lie very near the line *m m′* are undergoing induction very nearly as strongly as the actual pair that lie in that line; it would therefore naturally occur that the current might be simultaneously collected from more than one coil at once, either (1) by making the pieces of the commutators overlap, or (2) by connecting to the brushes that touch on the line *m m′* another pair having either a forward or a backward lead. If we now consider Fig. 293 we shall see this a little more clearly. This figure is a diagram of such an armature, the coils or loops being here represented merely by wavy lines.

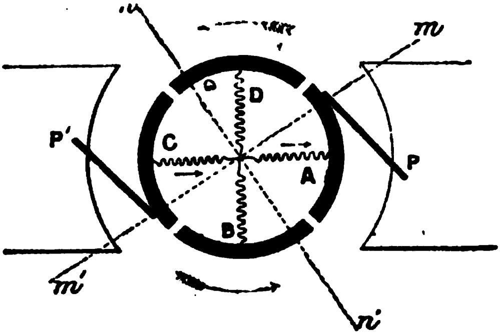
FIG. 292.



INDUCTION OF CURRENTS IN ARMATURE.

The wavy line A C may represent either a pair of coils such as there are in Fig. 293 on the ring, or may represent a single loop or group of windings round a drum. There is a pair of commutator-plates for A C, and another at right angles for B D. Coils A and C are just coming into the position of best action; they are delivering a current to the brushes P P, and this current will accordingly increase a little, and then decrease again. Meantime coils B and D are idle. If the four parts of the compound commutator each occupy just a quarter of the circumference, it is clear that when A comes into action its plane makes an angle of 45° with *m m′*, and that just as it leaves contact with the brush makes again an angle of 45° on the other side, being in contact in all intermediate positions; and so with each coil as it passes the brushes. There will be a momentary break of current and a spark as the two successive segments pass under the brush, unless the brush touches both at once. Remembering that Fig. 29, p. 38, represents the alternating currents from a single loop or pair of coils, and that Fig. 30, p. 38, represents the same currents rectified by the use of a simple two-part commutator, we shall be able to represent the effect of our new arrangement by some such diagram as Fig. 294. The angles marked below are reckoned from the neutral line *n n′*. When coil A has gone round 90° from this position, it is in the position of maximum induction: but because the segment A of the commutator is itself 90° in breadth, the current will be collected from 45° to 135°. The shaded portions of the curve show the discontinuous effect due to the coils A and C coming into circuit during two quarters of the rotation. The coils B and D come in

FIG. 293.

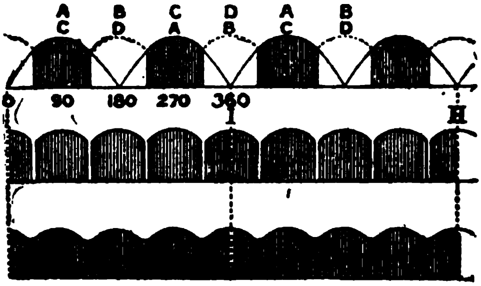


in the intervals, as indicated by the dotted lines. The induced currents will therefore present an approximate continuity depending on the arrangements of the commutator and the brushes. Fig. 295 represents the effect when there are gaps between the segments of the commutator; and it will be noticed that the currents, though all of the same sign, are discontinuous. If the brushes thus left contact with one segment of the commutator before the next come into contact there would inevitably be a considerable amount of sparking. Fig. 296 shows the result of making contact with one set before the other set is cut out; the induced current being now continuous, but with undulating fluctuations of strength. During the time when both sets of coils are in contact with the brushes, they are, of course, in parallel with one another. During this stage of the action the resistance of the armature is half as great as when one of the coils is cut out; but it is necessary to cut out the idle coil, otherwise some of the current from the active coil would flow back uselessly through the idle coil that was in parallel with it. During the time when the two sets of coils are in parallel they are not equally active. The induced electromotive-force is increasing in one and diminishing in the other; there is but a moment when they are equally active—when they make equal angles with *m m′*. At all other moments the higher electromotive-force of the more active

FIG. 294.

FIG. 295.

FIG. 296.



CURVES ILLUSTRATING THE PRODUCTION OF CURRENTS BY USING AN OPEN-COIL FOUR-PART ARMATURE.

coil tends to send a back-current through the less active coil: and the net electromotive-force with which they act on the brushes will be the mean of their two separate electromotive-forces.

From what has now been said, it will be clear that open-coil armatures may be constructed either as rings, drums, or disks. They may be arranged to run either in a simple or in a multiple magnetic field. The principal dynamos constructed upon this plan are the Brush machine and the Thomson-Houston machine: but there are a few others which also come within the category of open-coil dynamos.

Brush's Dynamo.—One of the best known and least understood of these machines is the Brush dynamo. Its general form, and the disposition of the field-magnets may be gathered from Fig. 297. The field-magnets are very substantially built. The magnet heads are insulated with sheets of the so-called vulcanised fibre, thoroughly varnished. The field-magnet cores are, however, first surrounded with a thin sheet of copper, soldered together at the edges so as to form a continuous tube or envelope. The object of this copper coating is to absorb the induced extra currents which otherwise would be set circulating in the core whenever a variation of the magnetism occurred. Over the copper envelope are wound four or five thicknesses of very heavy paper saturated with shellac varnish to insulate the wire from the iron. In some of the Brush dynamos there is a double winding, a shunt or "teazer" circuit being added to maintain the magnetism of the field-magnets when the main circuit is opened. The automatic regulator, described briefly in Chapter XXVII., is used with arc-lighting Brush machines.

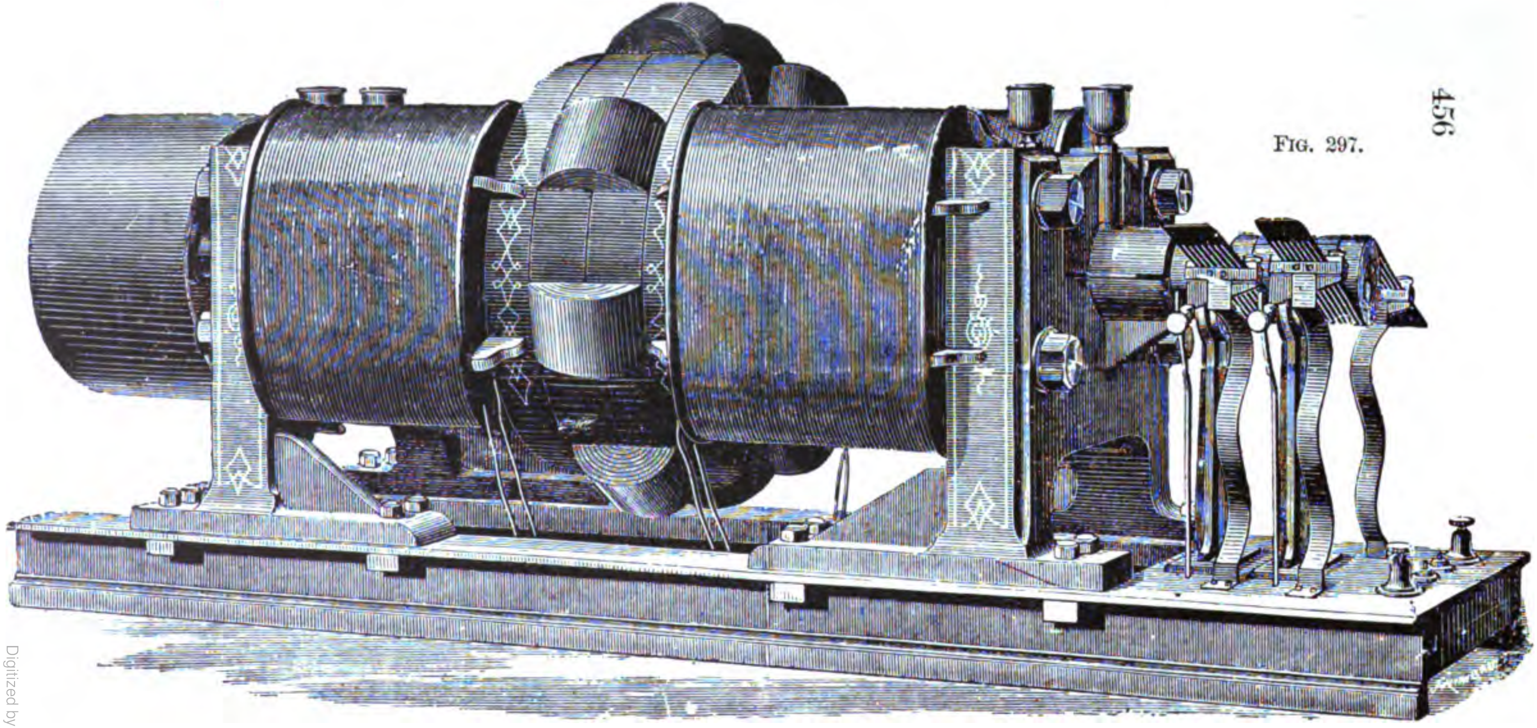
The armature—a ring in form, not entirely over-wound with coils, but having projecting teeth between the coils, like the Pacinotti ring—is a unique feature. Though it so far resembles Pacinotti's ring, it differs more from the Pacinotti armature than that armature differs from those of Siemens, Gramme, Edison, Bürgin, &c.; for in all those the successive sections are united in series all the way round, and constitute, in one sense, one continuous bobbin. But in the

Brush armature there is no such continuity. The ring itself was formerly made of malleable cast iron. The wire spaces were planed or milled out, and all angles and corners were carefully rounded. All iron parts which are to adjoin the wire of the "bobbins" are covered first with a layer of strong heavy canvas saturated with shellac varnish, and in the case of the armatures of the larger machines there are additional layers of tough paper saturated with shellac varnish. A sheet of strong cotton cloth inserted occasionally separates contiguous layers of wire from each other both in the armature bobbins and in the coils of the field-magnets. All the bobbins are wound by hand, in the same direction, and the inner ends of diametrically opposite bobbins are soldered together, and carefully insulated from all other wires and adjacent metal. The free outer ends of each pair of bobbins are separately carried along the shaft, through the journal, and connected to diametrically opposite segments of the commutator. In the "sixteen-light" machine the ring is 20 inches in diameter. In each of the eight coils there are about 900 feet of wire of ·083 inch gauge. Thus connected, the machine is adapted to deliver a current of ten amperes. By connecting the two bobbins of each pair in parallel, instead of in series with one another, the machine may be used to deliver a 20-ampere current. For electroplating, much stouter wires are used.

For each pair of coils there is a separate commutator. In the No. 7 size of machine, which is depicted in Fig. 297, there are eight coils on the armature, four commutators grouped in two pairs, and two sets of brushes. This size is commonly known as a "sixteen-light" machine, though it will, as now improved, supply from 24 to 25 arc lights.

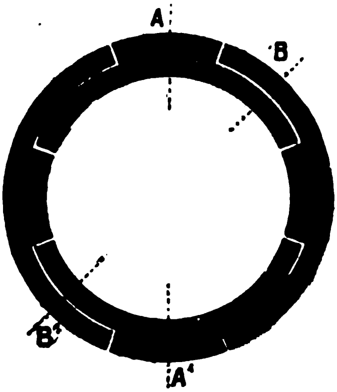
The larger Brush dynamo ("sixty-light" machines) have twelve coils upon the ring, connected as six pairs. There are three pairs of brushes, and three pairs of commutators, each pair being set one-twelfth of a rotation (30°) in advance of the next pair. These machines have the enormous electromotive-force of nearly 3000 volts; and, with the recent improvements, will supply 60 or more arc lights in a single circuit. They formerly supplied 40 lights only.

FIG. 297.



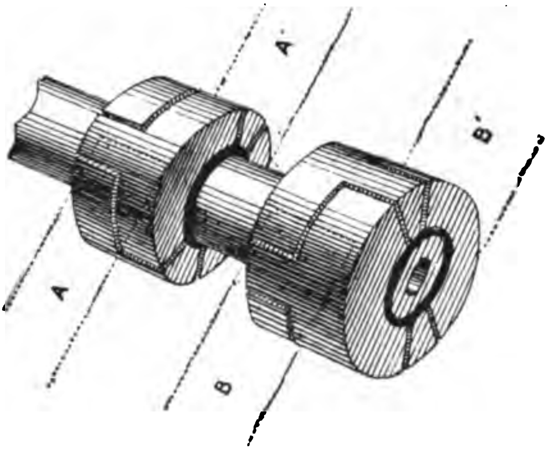
BRUSH DYNAMO, NO. 7 (TWENTY-FIVE LIGHT).

Fig. 298.



Pair of Overlapping Commutators.

Fig. 299.

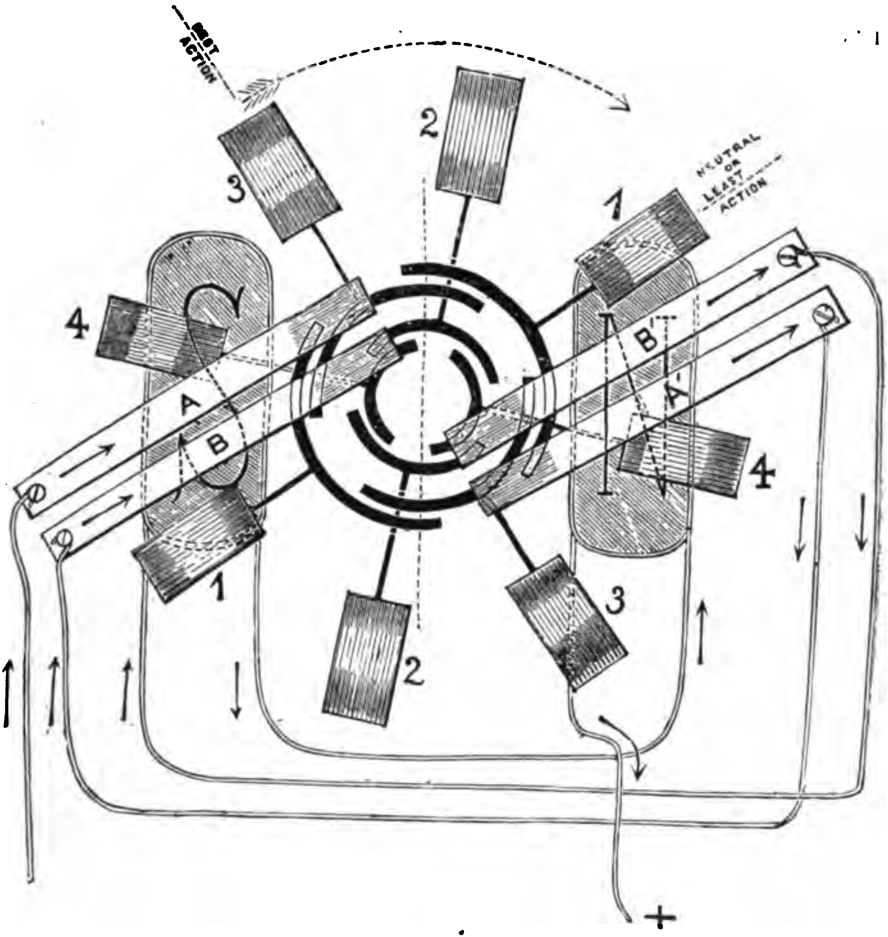


Brush Commutator for Armature wound with Four Pairs of Coils.

The brushes are arranged so as to touch at the same time the commutators of two pairs of coils, but never of two adjacent pairs; the adjacent commutators being always connected to two pairs of coils that lie at right angles to one another in the ring. Continuity is obtained in the currents by making the two parts of the commutator of each pair of coils overlap those of the commutator belonging to the pair of coils that is at right angles, one pair of brushes resting on both commutators. Fig. 298 is a diagram illustrating this device. Each pair of segments overlaps the other to the extent of 45°. Each of the two pairs of coils is thus cut out twice during a revolution; it is twice in circuit alone, as when the brushes are at A A′, and four times in circuit along with the pair that are at right angles, when the brushes are at

B B′. Fig. 299 shows the way in which the commutator is arranged in all eight-coil Brush armatures—that is, in machines for supplying from one to twenty-five arc lights. There are really four commutators here, corresponding to the four pairs of coils, grouped in pairs; one pair of commutators being set one-eighth of a rotation (45°) in advance of the other. It will be seen from this figure that while the brushes A A′ (shown in dotted lines) are receiving current from *one pair* of coils only, the brushes B B′ are at the same instant receiving the current from *two pairs* of coils which are joined in parallel with one another in consequence of both of their commutators touching the same pair of brushes. The arrangement may be still further studied by the aid of Fig. 300, which also illustrates the way of connecting the brushes with the circuit. In this figure the eight coils are numbered as four pairs, and each pair has its own commutator, to which pass the outer ends of the wire of each coil, the inner ends of the two coils being united across to each other (not shown in the diagram). In the actual machine, each pair of coils, as it passes through the position of least action (*i. e.* when its plane is at right angles to the direction of the lines of force in the field, and when the number of lines of force passing through it is a *maximum*, and the rate of change of these lines of force a *minimum*) is cut out of connection. This is accomplished by causing the two halves of the commutator to be separated from one another by about one-eight of the circumference at each side. In the figure it will be seen that the coils marked 1, 1, are "cut out." Neither of the two halves of the commutator touches the brushes. In this position, however, the coils 3, 3, at right angles to 1, 1, are in the position of best action, and the current powerfully induced in them flows out of the brush marked A (which is, therefore, the negative brush) into that marked A′. This brush is connected across to the brush marked B, where the current re-enters the armature. Now, the coils 2, 2 have just left the position of best action, and the coils 4, 4 are beginning to approach that position. Through both these pairs of coils, therefore, there will be a partial induction going on. Accordingly, it is arranged that the current on passing into B, splits, part going through coils 2, 2, and part through 4, 4, and re-uniting at the brush B′,

Fig. 300.



Connexions of Brush Dynamo.

whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A. (In some machines it is arranged that the current shall go round the field-magnets, after leaving brush

A′, and before entering brush B; in which case the action of the machine is sometimes, though not correctly, described as causing its coils, as they rotate, to feed the field-magnets and the external circuit alternately.) The rotation of the armature will then bring coils 2, 2 into the position of least action, when they will be cut out, and the same action is renewed with only a slight change in the order of operation. The following table summarises the successive order of connexions during a half-revolution:—

First position. (Coils 1, 1 cut out.)

$A - 3 - A'$; $B \left\langle \begin{matrix} 4 \\ 2 \end{matrix} \right\rangle B'$; **Field magnets – External circuit – A.**

Second position. **(Coils 2, 2 cut out.)**

$A \left\langle \begin{matrix} 1 \\ 3 \end{matrix} \right\rangle A'$; $B - 4 - B'$; **Field magnets – External circuit – A.**

Third position. **(Coils 3, 3 cut out.)**

$A - 1 - A'$; $B \left\langle \begin{matrix} 2 \\ 4 \end{matrix} \right\rangle B'$; **Field magnets – External circuit – A.**

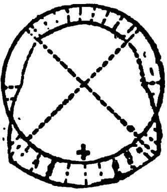
Fourth position. **(Coils 4, 4 cut out.)**

$A \left\langle \begin{matrix} 3 \\ 1 \end{matrix} \right\rangle A'$; $B - 2 - B'$; **Field magnets – External circuit – A.**

From this it will be seen that whichever pair of coils is in the position of best action, is delivering its current direct into the circuit; whilst the two pairs of coils which occupy the secondary positions are always joined in parallel, the same pair of brushes touching the respective commutators of both; and the remaining pair of coils being cut out.

One consequence of the peculiar arrangement thus adopted is, that measuring the potentials round one of the commutators with a voltmeter gives a wholly different result from that obtained with other machines. For one-eighth of the circumference on either side of the positive brush, there is no sensible difference of potential. There then comes a region in which the potential appears to fall off, but the falling off is here partly due to the shorter time during which the adjustable brush connected with the voltmeter and the fixed positive brush are both in contact with the same part of the commutator. Further on there is a region in which the voltmeter gives no indications, corresponding to the cut-out position; and again, on each side of the negative brush, there is a region where the polarity is the same as that of the negative brush. Fig. 301 is a diagram of a six-light Brush taken at one commutator, the main + brush being, however, allowed to rest (as in its usual position) in contact with both this commutator and the adjacent one.

FIG. 301.

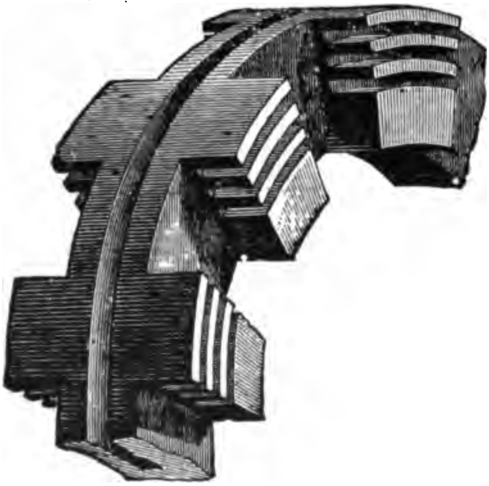


POTENTIALS AT COMMUTATOR OF BRUSH DYNAMO.

From the foregoing considerations, it will be clear that the four pairs of coils of the Brush machine really constitute four separate machines, each delivering alternate currents to a commutator, which commutes them to intermittent unidirectional currents in the brushes; and that these independent machines are ingeniously united in pairs by the device of letting one pair of brushes press against the commutators of two pairs of coils. Further, that these paired machines are then connected in series, by bringing a connexion round from brush A′ to brush B.

The core of the Brush ring, as formerly made, was of malleable cast iron channelled at the sides, so as in some degree to obviate eddy currents. The coils are wound in deep radial recesses. The form of the ring, with its coils, may be discerned in Fig. 297, and the channelled cast-iron ring itself is shown in Fig. 302. The solid masses of iron in this now obsolete form of armature gave rise to wasteful eddy currents, the production of which heated the ring and absorbed considerable power. In the newer Brush machines a ring is employed which is built up of a thin iron ribbon 1·5 millimetres thick. Figs. 303 to 305 show its construction, though in reality a larger number of pieces of thinner iron than is shown are used. The ribbon is wound upon a circular foundation ring A′, projecting cross-pieces of the same thickness and of the form shown in Fig. 305 (and also marked H in Figs. 303 and 304) being inserted at intervals to separate the convolutions, admit of ventilation, and form suitable projections between which to wind the coils. In the larger armatures there are 45 turns of the ribbon. It is secured by well insulated radial bolts. The gain in coolness

FIG. 302.



CORE OF BRUSH RING (Old pattern).

FIG. 303.

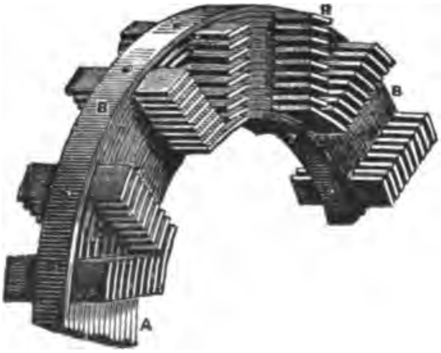
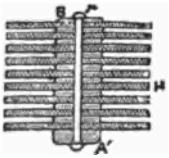


FIG. 304.



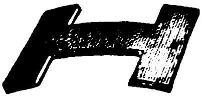


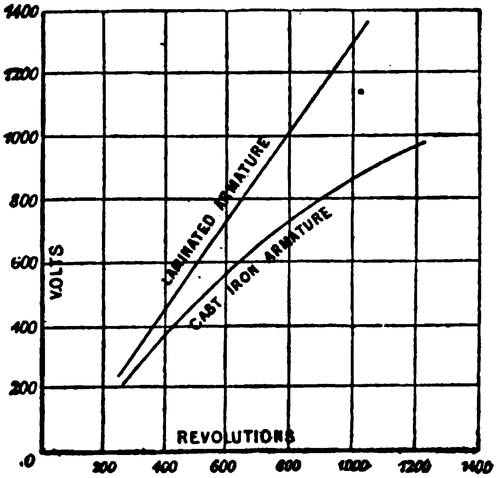
FIG. 305.

CORE OF BRUSH RING (New pattern).

is great; and the old machine, which formerly supplied 40 arc lamps, when provided with the new ring can supply 65 lamps at the same speed as before. The smaller 16-light machine with an armature of the new type lights 25 lamps, showing that the deleterious reactions have been fairly eliminated; and it may even be run at higher speeds with perfect safety.

The most striking way of realizing the great improvement which has thus been made is to compare the speeds required to develop equal electromotive-forces in the two machines. The experiments were made with identical machines. Both armatures were of the same size, with same length and weight of wire; and the field-magnets were identically excited with a 10-ampere current. The results are shown in the two curves of Fig. 306. At 800 revolutions the old cast-iron armature gave about 730 volts: the new laminated armature gave over 1000 volts.[1]

Fig. 306.



Curves of Old and New Patterns of Brush Machine.

Some large shunt-wound Brush machines have been recently constructed for electro-metallurgical purposes. The largest of these,[1] having an armature 42 inches in diameter, running at 405 revolutions per minute, gave 3200 amperes at 83 volts. This colossal machine weighs nearly 10 tons, the weight of copper on the field-magnets being 5424 lb., that on the armature 1600 lb. This is at the rate of 1 lb. of copper on the armature for every 160 watts of output; or 43 watts for every 1 lb. of copper on the machine.

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[1] More surprising still, the power absorbed in driving the old armature giving 730 volts was 17 horse-power, whilst that absorbed in driving the new, giving 1020 volts was only 16 horse-power. The old armature could not be run above 800 revolutions per minute without dangerous heating. The new armature may be safely run at a much higher speed, without risk of heating or other danger.

Some elaborate tests on Brush dynamos, with two different patterns of armature, were made[2] in 1889 by Mr. Murray of Melbourne. These showed commercial efficiencies of about 69·8 per cent. in machines with core-plates 0·05 inch thick, and of about 78 per cent. in those with core-plates 0·022 inch thick. The values of B attained were about 4800 in field-magnet cores and 27,000 in the armature cores. The fluctuations of the current were about 1·5 per cent.

Some drawings of a small model Brush dynamo are given in Plate XVI.

The automatic governor used for maintaining the constancy of the current is described in Chapter XXVII. on Regulators.

Thomson-Houston Dynamo.—This machine, which is equally remarkable, was designed by Professors Elihu Thomson of Lynn and Edwin J. Houston of Philadelphia. Its spherical armature is unique among armatures; its cup-shaped field-magnets are unique amongst field-magnets; its three-part commutator is unique among commutators. A general view of the machine is given in Fig. 307, and a sectional one in Fig. 308. As will be seen from these cuts, the field-magnet core consists of two flanged iron tubes furnished at their inner ends with hollow cups cast in one with the tubes, and accurately turned to receive the armature. Upon the tubes are wound the coils C C′, and afterwards the two parts are united by means of a number of wrought-iron bars *b b*, which constitute the yoke of the magnet and at the same time protect the coils. The magnets are carried on a framework, which also supports the bearings for the armature

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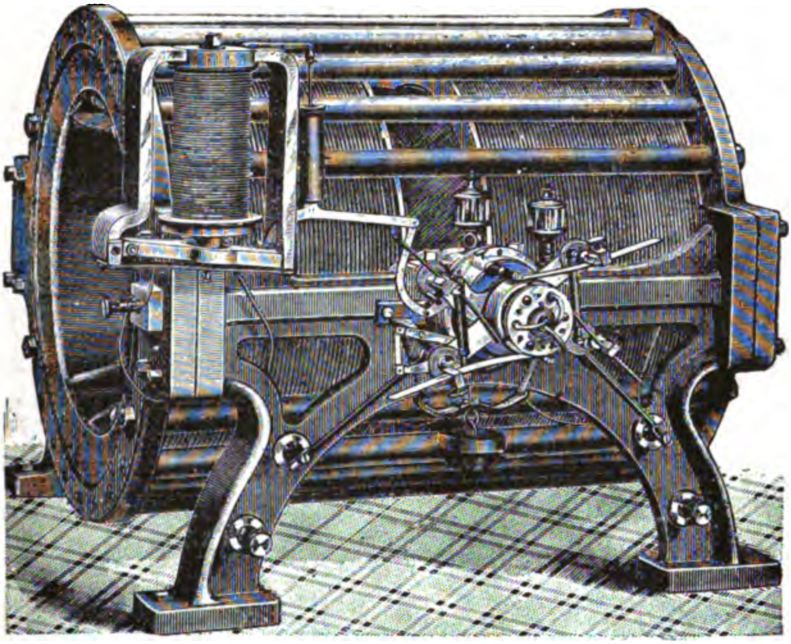
[1] See paper by Prof. Thurston, in *Journal of Franklin Institute*, Sept. 1886; or see *Electrician*, xvii., 469, 1886.

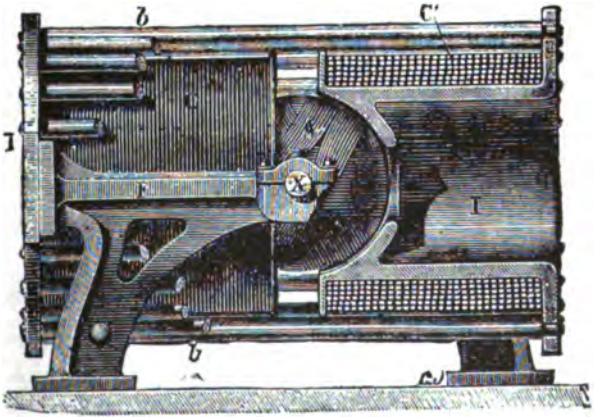
[2] *Journal Inst. Electrical Engineers*, xvii. 710, Nov. 1889.

FIG. 307.



THOMSON-HOUSTON DYNAMO.

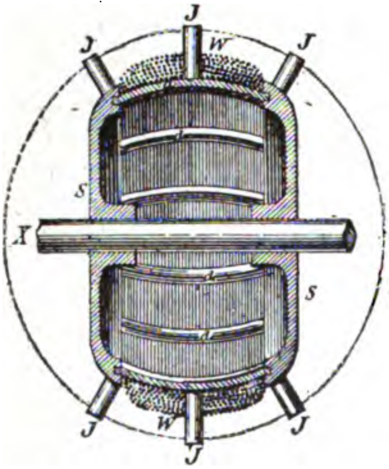
FIG. 308.



THOMSON-HOUSTON DYNAMO (part Section).

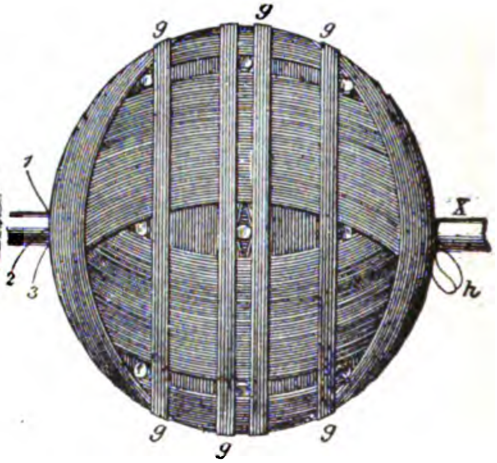
shaft X. The armature, which is spheroidal rather than spherical, is constructed as follows: Upon the shaft are keyed two concave iron disks S, S (Fig. 309), the space between them being bridged by light ribs of wrought iron, *d*, *d*. Wooden pins J, J, are driven at intervals into appropriate holes drilled in the iron shell to facilitate the winding of the coils. The winding itself is very remarkable. There are but three coils. The inner ends of these are united together (at *h*, Fig. 307), *and not connected to any other conductor.* The three wires are then wound over the shell (which is covered with varnished paper) in three sets of windings making 120° with one another, and arranged to be at equal average distances from the core by the following device. Beginning at the junction at *h*, half the No. 1 coil is wound. Then the armature is turned through 120° and the No. 2 coil is wound on to half its length. Then coil No. 3 is wound, starting from *h*, and finished off at 3. Then the second half of No. 2 is completed; lastly, the second half of coil No. 1. The three coils are, therefore, on the average, equidistant from the iron core: their overlapping makes the external form nearly

Fig. 309.



Thomson-Houston Armature (Section).

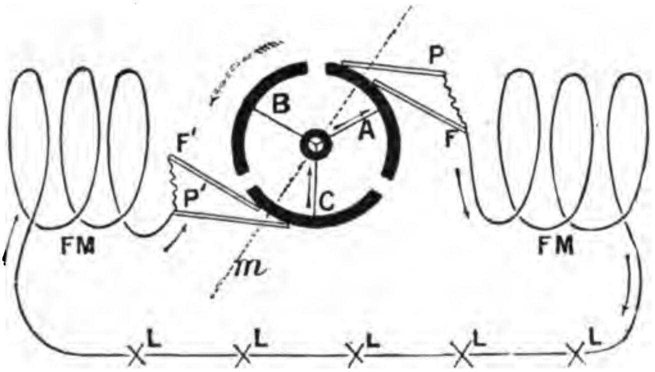
Fig. 310.



Thomson-Houston Armature.

spherical. They are held in place by the binding wires *g g*. Quite recently a new armature has been introduced, also having three coils, but ring-wound so that there is no overlapping. Winding and repairing are thereby much facilitated. The connexions of the three circuits remain as before. When this armature is rotated within the cavity between the cup-shaped poles alternate currents are generated in each separate coil in turn, and it now remains to consider how these alternate inductions are rectified and combined by the commutator. In the diagrams which follow, the rotation is represented as left-handed, as viewed from the commutator-end of the shaft, as it is in practice. Fig. 311 represents the arrangement

Fig. 311.



Commutator and Circuit of Thomson-Houston Dynamo.

in diagram. The three coils represented diagrammatically by the three lines A B C, are united at their inner extremities, each outer end being led to one segment of a three-part commutator. There are two positive brushes P and F, and two negative brushes P′ and F′. The current delivered to P and F first flows round one of the field-magnets, thence goes to the outer circuit of lamps, returning through the other field-magnet to P′ and F′. The reader should now compare this diagram with Fig. 292, p. 451, and observe that in that figure the neutral line *n n′* divides the rotation obliquely into two halves, the induced currents flowing outwardly from centre to commutator in all coils that are rising through the right-hand half of this obliquely divided circle; and inwardly from commutator to centre in all coils descending through the left-hand half of the rotation. Accordingly in Fig. 311 there will be an outward current in A and an inward one in C; B being for the moment cut out of circuit as it passes through the neutral position. Continuity is obtained by the device mentioned on p. 451, of having the second pair of brushes F F′ following the pair P P′. In this position of the armature A and C make about equal angles with the line of maximum action *m m′*, hence the two electromotive-forces in these coils are for the moment about equal, but that in A is increasing, that in C decreasing. As these coils are now in series, their separate electromotive-forces are of course added together. A moment later we shall have arrived at the state of things represented in Fig. 312, which is a twelfth of a turn advanced. A is now

Fig. 312.

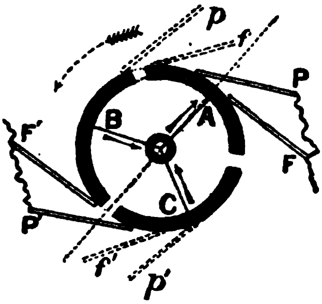
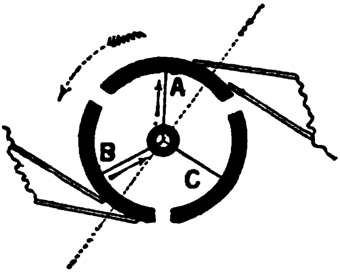
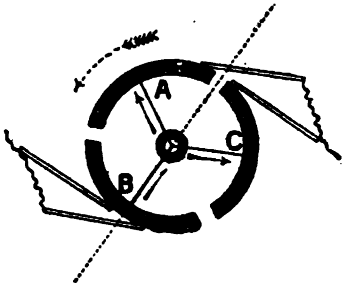


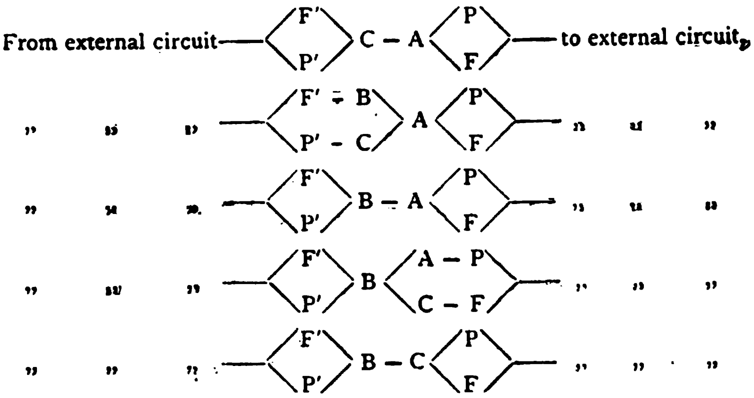
Fig. 313.



in the position of maximum induction; C is rapidly approaching the neutral position but is not yet cut out; B has again begun to have electromotive-force induced in it, and has just come into circuit. B and C are in parallel with one another and in series with A. The next twelfth of a turn brings us to the stage shown in Fig. 313. C is now at the neutral position and is out of circuit, A has passed the maximum on one side and B is approaching the maximum on the other; and they are in series. Another twelfth of a turn and we arrive at Fig. 314. A is fast approaching the neutral position; B is at its maximum; C has passed the neutral stage, and has just come into circuit again by touching the positive following brush. Another instant and C will occupy the place where A was in Fig. 308, a whole third of a revolution having been completed, and the actions recommence, A occupying the place of B, and B that of C. The following table exhibits the round of changes during a third of a revolution:—

Fig. 314.



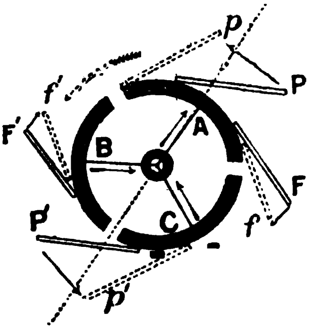


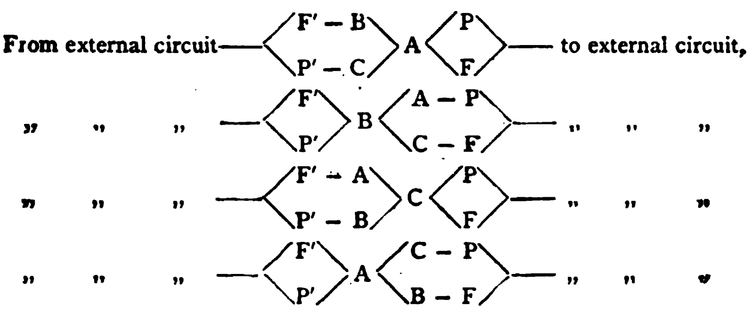
and so forth.

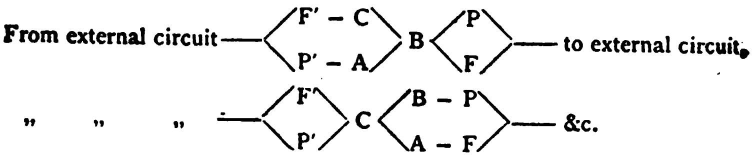
If the width of the gaps between the segments of the commutator be equal to the width between the adjacent brushes, each coil will be out of circuit whenever it is more than 60° from the position of maximum action, and the time during which any two coils are in parallel will be practically nil. But if the following brushes F F′ are at a considerable angle—about 60° in practice—behind the brushes P P′, there will be considerable duration of the stage during which two coils are in parallel.

The regulation of this machine to maintain a constant current is accomplished by an automatic shifting of the brushes. At first the inventor adopted a method of "forward" regulation, the brushes being set at only 35° in advance of one another, and being both shifted forward whenever the current exceeded its proper strength. The effect of this will be seen by considering the dotted lines $p\,p'$ and $f\,f'$ in Fig. 312. Clearly, if p maintained contact with B *after* it had passed the neutral line, its electromotive-force would tend to diminish that of A which is in contact with f. This method was found in practice unsatisfactory, and has been abandoned. The actual method now used is termed "backward" regulation. In this system the following pair of brushes F F′ is shifted backward to $f\,f'$ as shown in Fig. 315, whilst at the same time the leading brushes P P′ are shifted forward through an angle one-third as great towards $p\,p'$. If, as stated above, the brushes are 60° apart under normal conditions, there will be exactly 120° on either side between the positive brushes P F and the negative brushes P′ F′; and as 120° is the exact length of each segment of the commutator, no coil will be cut out, and parallelism will subsist between two coils through angles of 60°: that is to say, there will always be two of the three coils in parallel with one another and in series with the third coil. The six stages of change will be:—

FIG. 315.





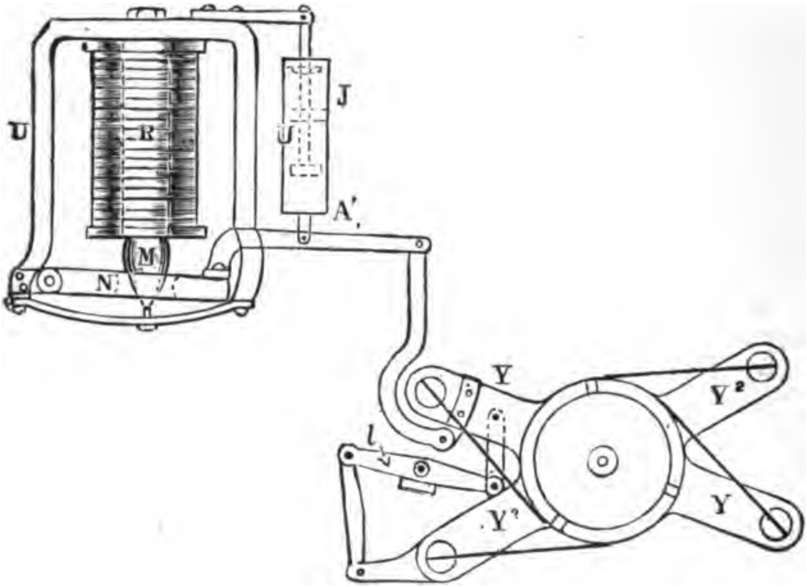


Now suppose the current to become too strong owing to reduction of number of lamps in circuit, the following brushes are made to recede. This will shorten the time during which any single coil in passing through the maximum position is throwing its whole electromotive-force into the circuit, and will hasten the moment when it is put in parallel with a comparatively idle coil. During such movements of regulation the whole machine is momentarily short-circuited six times during each revolution by F receding so far towards P′, and F′ receding so far towards P, as that both touch the same segment of the commutator at one instant. The action is assisted by the slight advance of P and P′, but the main object of this advance is to lessen the sparking. If the current is too weak, then the pairs of brushes must be made to close up, thereby reducing the time during which the most active coils are in parallel with those that are less active.

Regulating Gear.—This motion of advance and retreat is accomplished by the simple mechanism shown in Fig. 316. The brushes are fixed to levers Y Y and Y_2 Y_2 united by a third lever *l*. The automatic movement is imparted by the regulating electromagnet R, whose pole M, of paraboloidal form, attracts its armature N according to the current flowing round it. A dash-pot J, attached to the arm A, prevents too sudden motions. The circuits which operate this mechanism are further shown in Fig. 317. Normally the electromagnet R is short-circuited through a by-pass circuit, and only acts when this circuit is opened. At some convenient point of the main circuit two solenoids are introduced, their cores being supported by a spring; and the yoke of the cores operates the contact lever S. If the current becomes too strong this contact is opened, and the regulating magnet R raises the arm A. During running the lever S is continually vibrating up and down, and so altering the brushes to the requirements of the circuit. A carbon shunt of high resistance *r* is added to minimize the destructive spark at S.

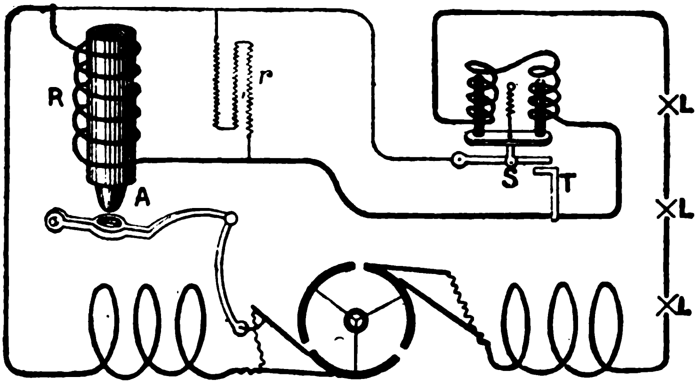
It might be expected that with only three parts to the commutator, the sparks occurring as the segments pass under the brushes would speedily destroy the surface. This difficulty has been met by Prof. Thomson in the boldest manner.

FIG. 316.



REGULATING MAGNET AND GEAR OF THOMSON-HOUSTON SYSTEM.

FIG. 317



CIRCUITS OF THOMSON-HOUSTON SYSTEM.

By means of a small mechanical blower, fixed upon the shaft behind the commutator, intermittent blasts of air are blown exactly at the right moment so as virtually to blow out the spark. The three segments of the commutator are separated by gaps; and in front of each of the leading brushes (as shown in Fig. 307) there projects a nozzle which discharges a blast, alternately, three times in each revolution.

The normal current for this dynamo is 9·6 amperes, or 6·8 amperes, though they are also wound for stronger currents. One of the larger machines will maintain 63 arc lights in a single circuit, with an electromotive-force of 3000 volts. The ordinary machine supplying 34 arc lamps at 45 to 46 volts each with a current of 9·6 amperes, has an internal resistance of 10·5 ohms in the armature and 10·5 ohms in the field-magnets. The armature is 23⅛ inches in external diameter; its wire being of 0·081 inch gauge. That of the field-magnets is 0·128 inch gauge. The usual speed is 850 revolutions per minute; but the peculiar arrangements for automatic regulation render the machine nearly independent of irregularities in the speed. There is in the armature about 1 yard of wire for every 0·53 volt of the induced electromotive-force. The ratio of weight of copper to iron in these dynamos is very high compared with that of many machines, being 1 of copper to 2·25 of iron.

Professor E. Thomson has also designed, for supplying large currents at low potential, a form of dynamo which is outwardly of similar structure to the machine described above. But in this new machine, which is intended for incandescent lamps in parallel, the spherical armature is wound as a closed-coil in sixteen sections. The field-magnets are much more massive, and the output of the machine more than five times as great in proportion to its size. It is compound-wound; the series coils being wound on a separate frame over the armature.

Advantages of Open-coil Dynamos.—The two great typical open-coil dynamos—those of Brush and of Thomson-Houston—appear to have certain qualities which render them specially applicable as constant-current dynamos for arc-lighting. Three-quarters of all the arc-lights in the world are run by one or other of these machines. It would seem that the closed-coil dynamos, whether of the ring or of the drum type, are not so well adapted for furnishing the very high electromotive forces needed for this work. The commutator, with its many parallel bars insulated with mica or papier-maché (which is the indispensable adjunct of the closed-coil armature), rapidly deteriorates when exposed to the inevitable sparking and wide alterations of lead which are inseparable from the constant-current method of working. For this method of distribution of electric energy, nothing will stand wear and tear so well as the simple air-insulated commutators described in this chapter. As a partial set-off against these advantages may be reckoned the fluctuations in the currents which arise from the employment of so few coils or groups of coils.

Fluctuations of Current in Open-coil Armatures.—The calculations of the fluctuation given in Chapter IX., p. 221, for closed-coil armatures are also applicable to open-coil armatures, provided there is no cutting out of coils. When idle coils are cut out, the fluctuations are less marked, but the calculations are less simple. That such fluctuations exist is abundantly verified by the interference of arc-light circuits with neighbouring telephone lines in which they induce buzzing noises. Rapidly fluctuating currents are affected by the self-induction of any electromagnets in the circuit, which always tends to tone down the rapid fluctuations and steadies the current.

A special study of the curves of induction in the armature of a Thomson-Houston arc-light machine has been made[1] by Mr. Milton E. Thompson, who found the total current at full load to fluctuate between five and eight amperes, six times in each revolution; the mean current being 6·8. The fluctuations of electromotive-force in each individual coil were very remarkable; the curves being singularly irregular, falling to near zero twelve times in each revolution.

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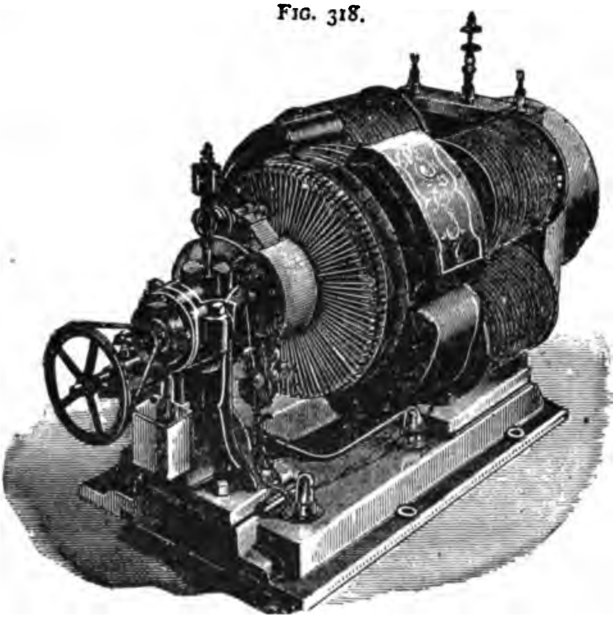
[1] *Electrical World*, xvii. 392, 1891, and *Electrical Review*, xxviii. 773, 1891.

OTHER ARC-LIGHT MACHINES.

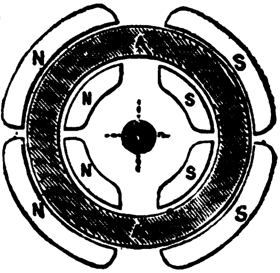
Sperry's Dynamo.—An arc-light dynamo with a Gramme armature is that of Sperry, Figs. 318, 319, the distinguishing feature of which is the use of internal as well as external pole-pieces. One of these machines, shown, in 1889, at Paris, gave ten amperes at 620 volts, when running at 1000 revolutions per minute. The ring-core was of $10\frac{9}{16}$ inches internal and $13\frac{1}{2}$ inches external diameter, and $6\frac{1}{4}$ inches long. The commutator had 72 bars; and the winding consisted of 72 sections of 40 turns each in four layers. The clearance space outside the binding wires was about $\frac{5}{32}$ inch. The inventor claims[1]

FIG. 318.



SPERRY'S ARC-LIGHT DYNAMO.

FIG. 319.



SECTION OF SPERRY DYNAMO.

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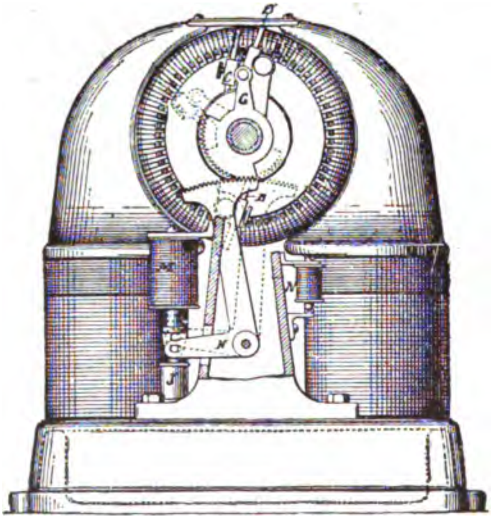
[1] See appendix to paper by Esson, in *Journal Inst. Electrical Engineers*, xix. 157, 1890.

that the brushes may be advanced from the position of full electromotive-force to even a position of zero voltage without sparking; the cross-magnetizing action of the armature being small compared with the power of the field-magnets.

Wood's Dynamo.—This also is a modified Gramme machine,[1] supplying 9·6 amperes at 2640 volts, at a speed of 875 revolutions per minute. There are 120 sections with 72 turns in each, and a cross-section of iron in the ring of 14 sq. inches. To obviate sparking, there is an auxiliary brush placed 5 to 10 sections ahead of the collecting brush; and the voltage is varied by a device which shifts the brushes forward. The largest arc-lighting station in the world, that at St. Louis, Missouri, is supplied with 53 of these dynamos, each capable of feeding 60 arc lamps.

FIG. 320.



WOOD'S DYNAMO.

Ball's Dynamo.—For ten years there has been extensively used in the United States a machine having two Gramme armatures side by side on one shaft, with a magnetic circuit of very singular design. To each armature there is only one pole-piece, so that the magnetic lines which enter the ring on one side have to find their way out across a wide irregular gap, with the consequence that there is great magnetic leakage and waste of magnetizing power. The disadvantage of this method of using a bad magnetic circuit was pointed out in the earlier editions of this work; and experiments were cited showing how, with a rational arrangement to magnetize one armature between two pole-pieces instead of half magnetizing two armatures with one pole-piece each, a single armature might yield as high an electromotive-force as do the two. It remains, however, to be stated that in spite of these imperfections of design, the Ball machine has given great satisfaction, its construction having been evidently carried out with good engineering skill.

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[1] See *Electrical World*, xii. April, 23, 1887, and xiv. 54 and 260, 1889; also xvii. 4, 1891.

Edison's Municipal Dynamo.—A special machine for series lighting, by means of incandescent lamps, is used by the Edison Company under this name.[1] There are several sizes of machines for currents of 9, 16, 32, and 48 amperes respectively. The smallest of these has three circuits, each to supply a three-ampere current to a separate row of lamps, the volts being 1200 at 1600 revolutions per minute.

Phœnix Arc Dynamo.—Mr. W. B. Esson has designed arc-light dynamos[2] for Messrs. Paterson and Cooper, using Gramme ring armatures; and finds no difficulty in constructing them from 800 up to 1500 volts. Some are of the form shown in Plate V., but are wound somewhat differently for constant-current work; others have a double magnetic circuit. As the armature is wound with many turns of fine wire, there are many turns to each section, which therefore possesses considerable self-induction, and requires a large electromotive-force to reverse the current in it in the act of commutation. If, therefore, the regulation is to be effected by shifting forward the brushes, it is clear that in every position, from minimum to maximum of the range, the magnetic field in the gap must be adequate; and as the coefficient of self-induction is nearly constant, the field in the gap-space must also be nearly constant. In other words, the iron of the field-magnet may be reduced in quantity, but excited to a high degree, so as to be more constant in its magnetization.

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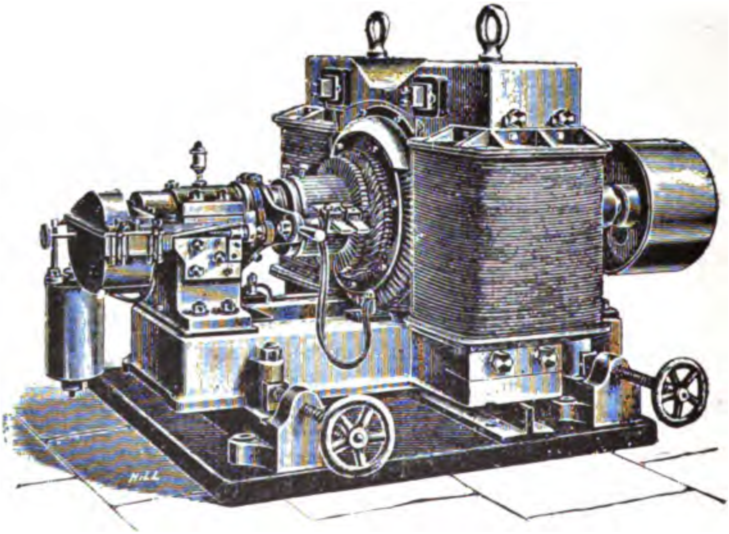
[1] *Electrical Review*, xxv. 209, 1889.

[2] *Journal Inst. Electrical Engineers*, xix. 161, 1890.

Statter's Dynamo.—Another example of a constant-current dynamo, with an automatic regulator to shift the brushes, is afforded by Statter's machine, in which, by a careful shaping of the pole-faces, a disposition of the magnetic field is obtained which permits the machine to run sparklessly. The mechanism which moves the brush consists[1] of a toothed wheel, actuated by one or other of two pawls driven from the shaft by an eccentric. A solenoid in the main circuit controls the action of the pawls, and so shifts the brushes forward or back as may be needed to keep the current constant.

FIG. 821.



STATTER'S CONSTANT CURRENT DYNAMO.

Schuyler's Dynamo.—This machine has a drum armature wound in eight parts, and coupled up so that the coils are successively cut out at the neutral points.

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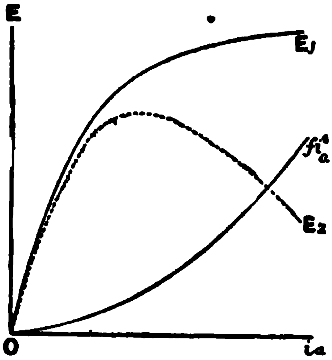
[1] *La Lumière Electrique*, xxx. 321, 1889; and Specification of Patent, 2825 of 1887.

Other Open-coil Dynamos.—Other forms of open-coil dynamos have been proposed by Bain, by Newton, and by Dr. Hammerl. The armature of the latter consists of a Gramme ring wound in sections, but having the inner ends of all the sections united together at a common junction, and their outer ends brought each to a separate bar of a collector. Sir Wm. Thomson has also suggested other forms in one of which the armature resembles a bicycle wheel. A disk dynamo of kindred design has lately been constructed by Poleschko, and is described in Chapter XIX.

Drooping Characteristics.—A method which, though not in itself securing constancy of current, is much followed in the construction of arc-lighting dynamos, should here be explained. Attention was drawn on p. 256 to the drooping form of the characteristic of certain series-wound machines. It is obvious that if this effect is sufficiently exaggerated, the drooping portion of the characteristic will correspond to the case of an approximately constant current. The drooping characteristic is important in promoting the steady working of arc lamps in the circuit. Suppose an arc lamp to be running on a series-wound dynamo under such conditions of working that the characteristic is ascending, any shortening of the arc will be followed by a reduction of resistance and a large increase of current. Whereas if the conditions of working are such as to fit to a point on the drooping part of the characteristic, any decrease in resistance in the circuit will result in a comparatively small increase of current.

The causes that tend to cause the characteristic of the series dynamo to turn down after reaching a maximum height are: (1) the demagnetizing effect of the armature current when there is a positive lead at the brushes; (2) the saturating of the iron of the armature core before that of the field-magnets; (3) the leakage of magnetic lines from the field-magnet; (4) the peculiar commuting arrangements in certain machines—for example, the open-coil dynamos mentioned previously—which make their effective electromotive-force vary greatly with the position given to the brushes; (5) high internal resistance, and self-induction. As the demagnetizing effect of the armature current is nearly proportional to the strength of the current and to the sine of the angle of lead, and as the sine of the angle of lead is itself nearly proportional to the armature current, it follows that the whole demagnetizing effect is nearly proportional to the square of the armature current. In Fig. 322 let the curve E_1 represent the electromotive-force (at a given speed) when the field-magnets are separately excited, the armature circuit being left open; this includes the effect of (2) and partially (3) above. On the same diagram a curve having ordinates proportional to i_a^2, and of such a magnitude as to represent the demagnetizing action of the armature current, may be plotted. Deducting the ordinates of this curve from those of curve E we get curve E_2, the drooping characteristic. The trouble with all machines of this class is the sparking at the brushes consequent on the variability of the angle of lead.

FIG. 322.



The effect of a drooping characteristic can to some extent be obtained by inserting in the external circuit a resistance of from 1 to 2 ohms. And this is preferable to having an internal resistance that would add to the heating of the armature. But such auxiliary resistance should be coiled on an iron core, since self-induction here is of value in steadying the current.

Constant Current Regulators.—A number of devices applicable to arc-light dynamos are described in Chapter XXVII.; amongst them being the "third-brush" regulator of Waterhouse for use in arc-lighting.

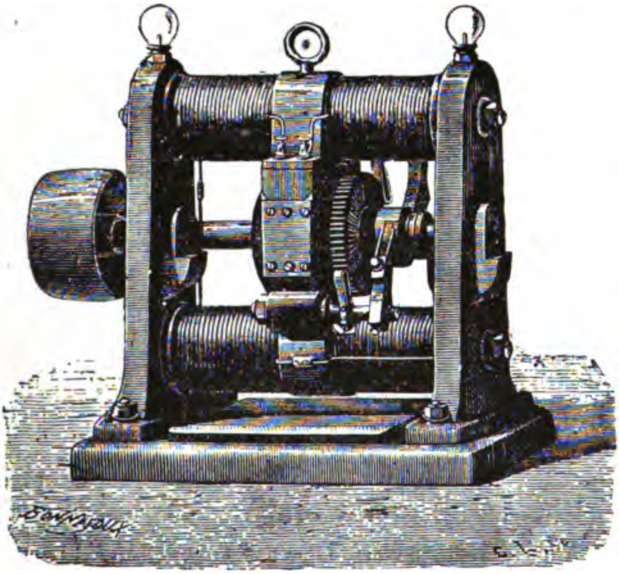
CHAPTER XVIII.

EXAMPLES OF MODERN DYNAMOS.—(Direct current.)

GRAMME DYNAMOS.

INNUMERABLE forms have been given to the Gramme machine at different dates since its appearance in 1871, varying from small laboratory machines with permanent steel magnets, such as are shown in Fig. 323, to large machines absorbing 30 or 40 horse-power. Those who desire more detailed information concerning the various patterns of Gramme dynamo should consult the earlier editions of this work, in which a number of forms were described. They

FIG. 323.



GRAMME DYNAMO, "A" PATTERN.

should also refer to the treatise of the late M. A. Niaudet, entitled *Machines électriques à courants continus, systèmes Gramme et congénères* (1881). Fig. 323 shows the ordinary "A" Gramme, the first pattern which came into commercial use, and which, with little alteration save general strengthening of the design, is in extended use to-day. Its characteristic features are the ring-armature, made of an iron wire core entirely overwound with coils (described p. 343), and the double-circuit field-magnet having consequent poles, a double north pole above, and a double south pole below the armature. The ring depicted in Fig. 35 (p. 43), is of more advanced construction, better built than the original type, and connected to the shaft by an internal gun-metal spider, instead of being driven on to a wooden hub; and the collector-bars are prevented from flying to pieces by the addition of an insulated ring shrunk on over their ends.

Another more recent form of Gramme dynamo is that depicted in Fig. 324, which has four *salient* poles, as distinguished from the consequent poles at the middle-points of the electromagnets. The field-magnets of this type are very simple, for the four cores, the external octagonal frame, and one of the two brackets which carry the shaft, are all cast in one piece (Fig. 324). The object of this is to secure a strong, light, and portable machine suitable for temporary lighting. The coils are wound on a separate mould, and slipped on and secured in their places. Some of these machines are constructed with two poles only. The weight of copper in them is relatively less than in the machines with consequent poles.

In 1885 a new form of field-magnet was adopted by M. Gramme, consisting of an inverted horse-shoe. In this

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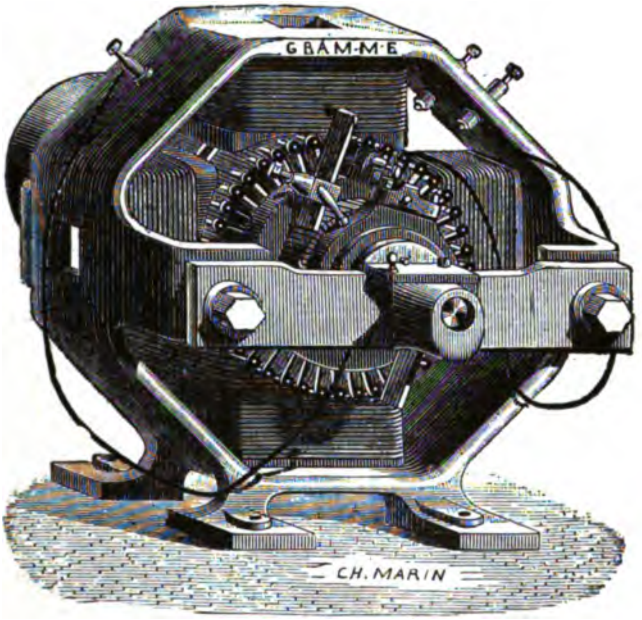
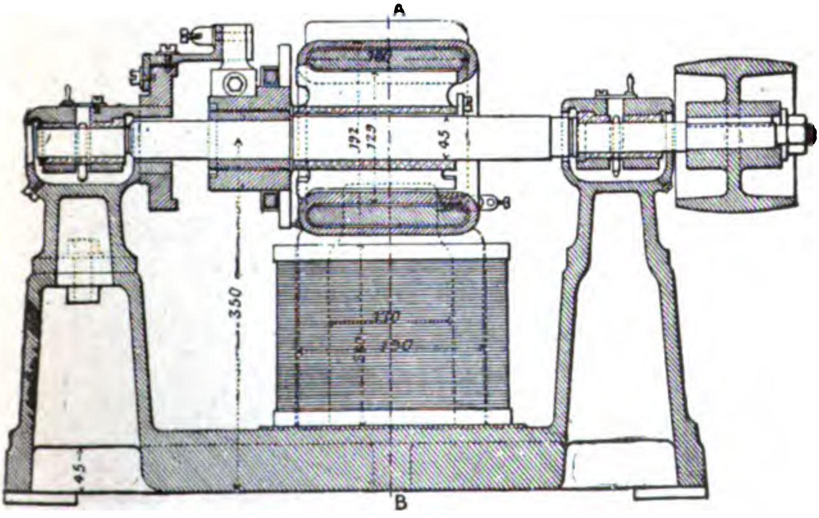
[1] Amongst these are the improved forms designed by M. Marcel Deprez, those designed by Mr. Hochhausen, and those made by the Fuller Company of New York; Mr. Wood of New York, has also perfected the design in many details. Other modifications have been made by M. Raffard, by MM. Sautter Lemonnier & Co., and by other French engineers: of these, some account is given in *Industries*, Nov. 5th, 1886. For an account of Gramme's historical exhibit in the Paris Exposition of 1889, see *Industries*, vii., 285, 1889.

FIG. 324.



FOUR-POLE GRAMME DYNAMO (1885).

FIG. 325.



GRAMME DYNAMO (*Type Supérieur*, 1885).

Fig. 326

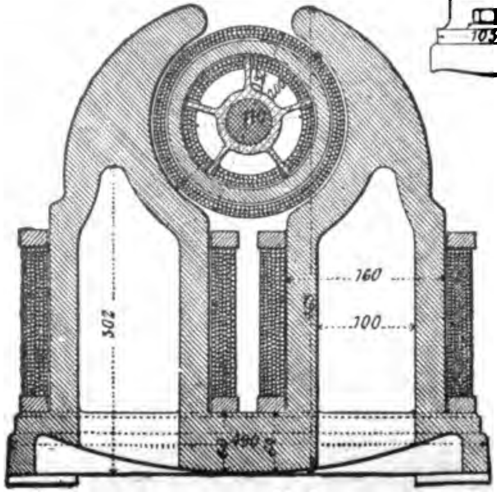


Fig. 328.

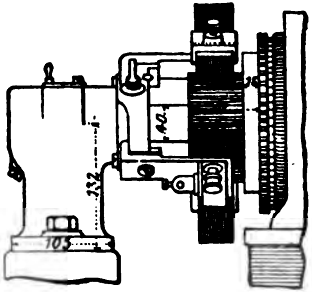
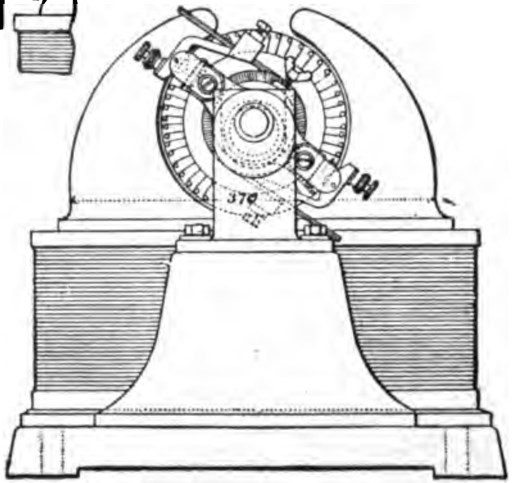


Fig. 327.



Section, End Elevation, and Details of Gramme Dynamo.

machine, sketches of which are given in Figs. 325–8, the bed-plate, the magnet-cores, the pole-pieces, and the supports of the bearings are of cast iron, all in one piece.

The field-magnet coils are wound on separate mandrils and then slipped over the cores between cheeks of insulating substance. The ring-armature is driven upon a spider of bronze, keyed to the shaft, its outer edges passing between the insulated copper coils and supporting the core, which is of laminated iron. The collector bars are held together by an external ring of bronze, well insulated from them. The details are shown in the figures, and it will be noted that the field-magnet cores are for some reason cast hollow. Fig. 328 shows the arrangements of the brush-holders. One of these machines, intended for an output of 40 amperes with a pressure of 110 volts, at a speed of 1400 revolutions per minute, had the following dimensions:—

Internal radius of armature core, 6·5 cm.; external radius, 9·15 cm.; axial length of core, 16 cm.; total sectional area of armature core, 80 sq. cm.; distance from armature core to pole-piece, 0·85 cm.; estimated area of each polar surface, 366 sq. cm.; sectional area of each iron magnet-core, 174 sq. cm.; estimated length of magnetic circuit within field-magnet, 81 cm.; commutator-bars, 60; total number of windings on the ring, 300; armature resistance, 0·174 ohm; shunt resistance, 46 ohms.

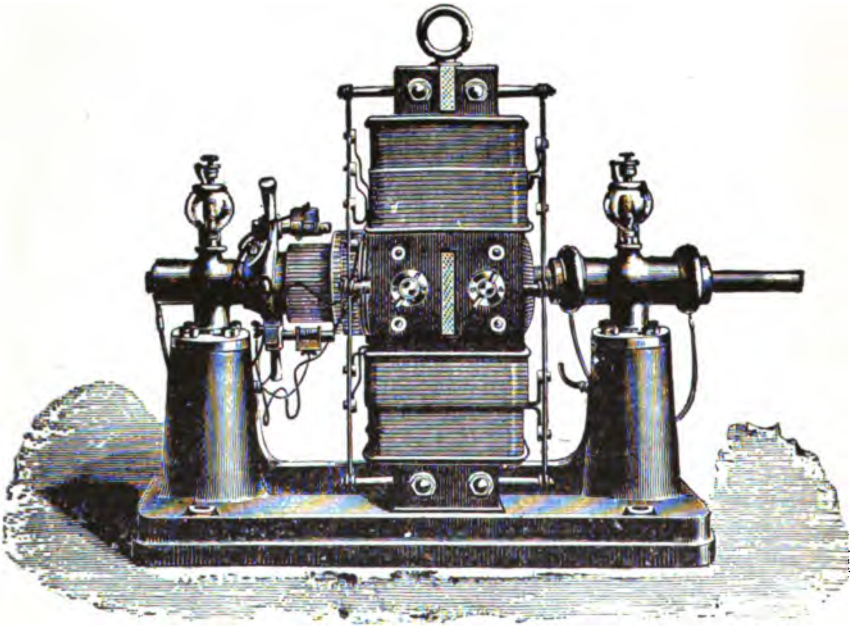
CROMPTON'S DYNAMOS.

Mr. R. E. Crompton, who pioneered many of the improvements in recent years, began with the now obsolete Bürgin form of ring-armature, for which, with the collaboration of Mr. Kapp, he subsequently adopted the cylindrical rings described on p. 349.

A general view of the Crompton dynamo is given in Fig. 329, which shows vertical field-magnets with a double magnetic circuit.

The armature windings, in the 1887 type, are formed of specially drawn copper wire of nearly rectangular section, cotton-covered, there being one turn of such wire to each segment of the commutator. The separate turns are bent to shape on proper formers before being placed on the ring, and are taped together in twos, so that when put in place they lie with the longer dimension of their rectangular section radial, so getting great depth of copper radially on the armature. The two turns lie side by side on the external periphery of the ring, but radially above one another at the internal periphery. The armatures are usually provided with driving-projections of insulated metal, inserted at intervals between the conducting wires; and after winding are strongly bound with binding-wires of tinned steel. In some of the most recent machines a single magnetic circuit only is employed. Another improvement useful in machines for furnishing large currents consists in dividing each conductor on the external periphery of the armature into two or more strips, which are crossed under one another at the middle and united together at their ends. Instead of such imbricated strips, rectangular

FIG. 329.



CROMPTON'S DYNAMO (1887).

bars of compressed stranded wires are now used in all large output machines. This construction greatly diminishes the eddy-currents which are set up in the conductors if they consist of single rods or bars.

A complete account of Mr. Crompton's successive stages of improvements[1] would occupy a volume in itself. Besides the improvements made in conjunction with Mr. Kapp on general design, p. 349, and more favourable use of iron in the armature, a number were made in conjunction with Mr. Swinburne on various modes of winding, p. 367, and on machines with conductors embedded in the core-disks. Then Mr. Crompton found that it was needless to insulate core-disks from spindle if they were separated from one another throughout their surfaces up to the periphery. Next came the question of driving-teeth, and the thick driving-disks mentioned on p. 349 were abandoned in favour of teeth of delta-metal or aluminium bronze, fitted into the substance of the compressed core. Then came the production of imbricated and compressed stranded conductors to obviate eddy-currents. Lastly, the adoption of multipolar series windings for drum armatures. With large four-pole machines for central-station lighting Messrs. R. E. Crompton and Co. have had great success. The construction of some of their large-output armatures is indicated in Figs. 265 and 266, on p. 370.

KAPP'S DYNAMOS.

Mr. Gisbert Kapp has designed various forms of direct-current dynamos, some having cylindrical ring-armatures, the more recent ones drum-wound armatures. The latest and best construction of 2-pole machine is that depicted in Fig. 330, being of the "over" type with the armature and shaft at the summit of the field-magnet. These machines are constructed by Messrs. W. H. Allen and Co., and by Messrs. Johnson and Phillips. In Plates I., II., and III. are given drawings of a 21-unit machine by the latter firm, giving 200

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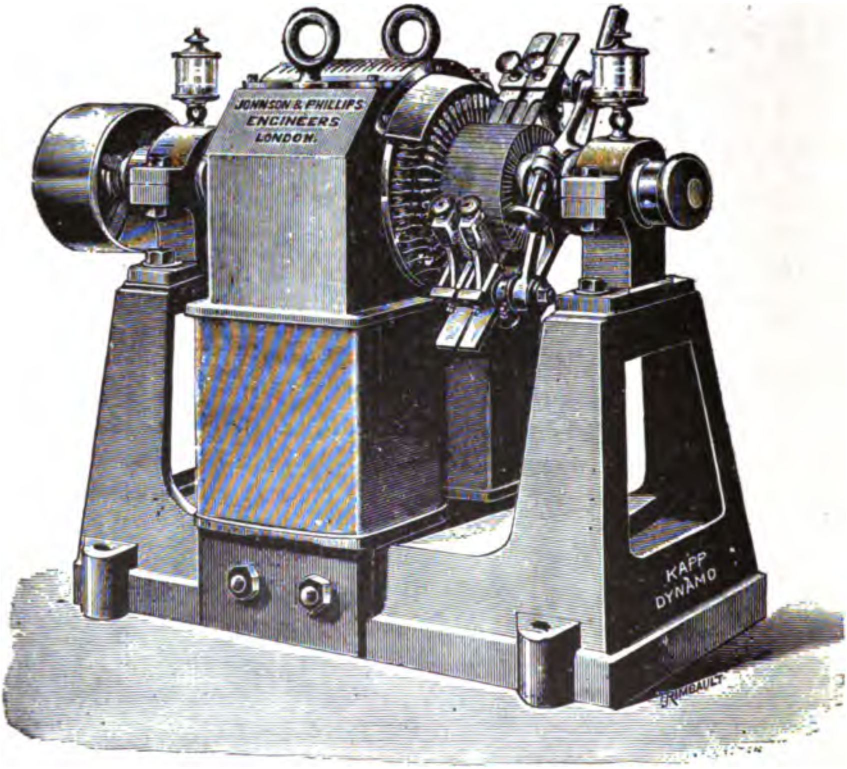
[1] See remarks by Mr. Crompton in *Proc. Inst. Civil Engineers*, lxxxiii 125, 1885; *Journal Soc. Teleg. Engineers*, xv. 546, 1886; and *Journal Inst. Elec. Engineers*, xix. 239, 1890, and xx. 308, 1891.

amperes at 105 volts at 780 revolutions per minute. The following are the data of this machine :—

FIG. 330.



KAPP DYNAMO.

Armature. Core 16″ long by $2\frac{3}{8}$″ deep, mounted on cast-iron spider. Area of iron in core, allowing for insulation between core-disks, 62·5 sq. in. External diameter $11\frac{1}{32}$″. Conductor 120 copper bars, each made of two parallel bars, 0·208″ × 0·110″ in section, united in parallel, affording 0·046 sq. in. sectional area. Connectors 120 copper semicircles with lugs ; depth $1\frac{5}{8}$″; thickness, 0·050″. Resistance (warm) 0·025 ohm. Commutator 60 parts.

Field-magnets. Diameter of bore, $11\frac{3}{16}$″. Shunt winding 11 layers, of 139 turns each, of 0·065″ diameter round copper wire, covered to a diameter of 0·080″, on each limb, and the two limbs connected in series. Total shunt turns 3058. Series winding 23 turns on each limb, of copper tape, 0·480″ wide by 0·130″ thick, and the two limbs joined in parallel. Resistance of shunt coils (warm) 30·8 ohms; of series winding 0·0079 ohm.

One peculiarity in this dynamo is the mode of driving the conductors of the armature. As shown in the section in Plate II., there are introduced at intervals between the core-disks, some thicker disks having ventilating apertures and projecting horns of steel. Around these steel horns are placed pieces of hard white fibre, as driving-horns; and as these project in alternate positions, the copper conductors cannot be laid straight, but are given a sinuous form. Plate II. also shows how the core-disks are clamped together by face-plates having ventilating perforations through them, the whole core being held up against a collar on the shaft by a screw-nut. The figures in Plates I., II., and III. also show the details of the brush-holder and rocker, the construction of the field-magnet, the arrangements of the bearings, and the pattern of lubricator employed.

Kapp's Multipolar Drum Dynamo for central-station lighting is shown on Plate IX., Fig. 2. This is a 6-pole machine with the armature windings grouped in parallel, or, if desired, in series, so as to need but two sets of brushes. The windings are of a cable of stranded insulated wire. The following are the data of the machine depicted:—

Output. 1100 amperes at 50 to 55 volts, at 460 revolutions per minute.

Armature. Length 12 inches; diameter 24 inches; number of conductors 224, connected in parallel grouping for six poles; nett armature resistance from brush to brush 0·00166 ohm (warm); commutator 112 segments; six sets of brushes at 60° apart.

Field-magnets. Cores, circular, 9 inches in diameter; pole-pieces 11¼ by 10 inches; exciting ampere-turns 8000 per magnet core.

A still larger 8-pole dynamo, having output of 134 kilowatts, is to be shown at the Crystal Palace. In this dynamo the pole-pieces are bevelled off only at the edge of pole-surface where the conductors approach the pole.

BROWN'S DYNAMOS.

These excellent machines, made hitherto at the Oerlikon Machine Works, near Zürich, are of several types. Of these, illustrations are given in Plates IV., VIII., IX., and X.

PLATE IV. *Glow-lamp Dynamo*, 28 *kilowatts.*—Output 400 amperes at 70 volts; 38 HP. at 400 revolutions per minute. This machine resembles the "Manchester" type, but is even more massive, and is now made with drum instead of ring winding. The core-disks are keyed to a long sleeve, and they are pierced to receive the copper conductors; the perforations being 12 mm. in diameter, sunk 1 mm. below the periphery. The thickness of the gap-space from iron to iron is thus reduced to. 2·5 mm. Core-disks, external diameter 51·4 cm., internal diameter 22 cm., thickness 0·6 mm.; number 570, insulated with paper. Total sectional area of iron in armature 480 sq. cm. Number of conductors around periphery, 80; commutator bars, 40; resistance of armature, brush to brush, 0·00525 ohm. Field-magnets, shunt wound with 2800 windings of wire, 3·2 mm. diameter; resistance 6 ohms, with about 1 ohm extra in series for regulation at above speed and output. Conductors passing through holes in armature are round copper 9·2 mm. in diameter. The end-connectors are of strip copper in two-legged pieces bent into spiral shape.

PLATE VIII. *Four-pole Ring Dynamo for Transmission of Power*, 170 *kilowatt dynamo.*—Output 270 amperes at 625 volts; 240 HP. at 500 revolutions per minute. These machines, of which two were shown in the Paris Exposition of 1889, stand nearly 8 feet high. They are ring-wound, with the windings external to the core-disks, as the construction with conductors embedded in perforations is not suitable for machines exceeding 100 volts. The cast-iron magnets are arranged radially, and are united by a very massive yoke ring, the lower half of which is cast in one piece with the frame and the supports for the bearings. The armature is

96 cm. in diameter, and 50 cm. deep. Core-disks, internal diameter 66 cm., external diameter 96 cm., thickness 0·6 mm. insulated with paper; net sectional area of iron in ring 660 sq. cm.; gap-space, iron to iron, 16 mm.; winding (generator) 400 turns of cable containing 19 strands of 1·3 mm. wire, wound in one layer externally and two layers internally; resistance, brush to brush, 0·025 ohm; cross-connexions, none; commutator 200 parts. Field-magnet coils in series with armature, and are each wound with 60 turns of 1 mm. copper sheet 30 cm. in width. Weights are as follows:—Frame and magnet cores 11,600 kilos, armature iron 1430, armature copper 132, armature complete 2420, magnet copper 1370. Total weight of complete machine, 15,700 kilos, or nearly 16 tons. At 500 revolutions per minute, it can be run at 250 HP. continuously night and day. If run in day only the current may be increased so as to work at 300 HP. Commercial efficiency at full load 93—94 per cent.

The machine used as motor, with the above generator, is nearly identical, the only differences being that there is slightly less iron in the armature, and there are only 364 windings with a 184-part commutator. Modified in this way the speed is constant, though the loss in the line varies with the load. Experience, which has dictated this proportion, leads, in this case, to the rule that for the motor the armature should be relatively less powerful, and the field-magnet relatively more powerful than in a generator.

A general view of this same machine is given in Plate IX., Fig. 1.

PLATE X. *Eight-pole Ring Dynamo for Electro-metallurgical Purposes.*—For the use of the aluminium industry Mr. Brown has produced 6-pole and 8-pole dynamos. That depicted in Plate X is a 300 HP. machine, working in the aluminium establishment at Neuhausen. It is fixed with its shaft vertical in continuation with the shaft of a vertical turbine. After working continuously day and night, with an average output of 3000 amperes, the commutator remains polished, for the machine runs sparklessly. The mode of cross-connecting each part of the ring winding to the two

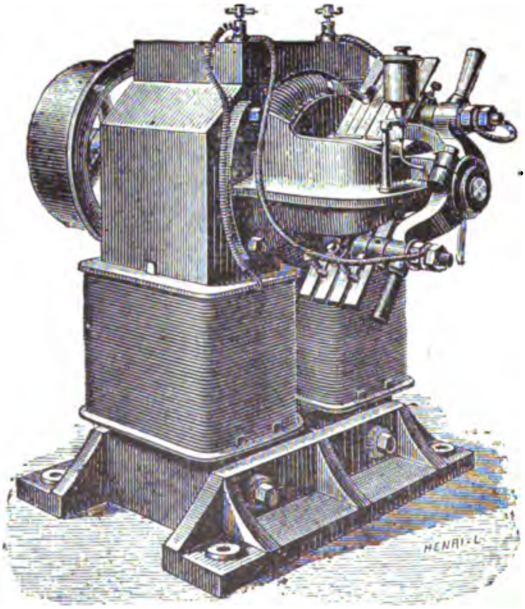
points of the commutator 45° distant is accomplished by bent two-legged strips of copper, as shown.

PATERSON AND COOPER'S DYNAMO.

The "Phœnix" dynamo, constructed by Messrs. Paterson and Cooper, from the designs of Mr. W. B. Esson, has also a modified cylindrical ring armature, built up of a number of very thin rings of Swedish iron separated from one another by paraffined paper and secured to two spiders by three bolts passing through indentations in the core-rings as shown in Fig. 245, p. 348.

There are no traverse gaps in the armature for ventilation, as there is little heating in this armature. These machines originally had a field-magnet with double magnetic circuit of forged iron and toothed core-rings. A Phœnix machine shown at the Antwerp Exhibition (of 65 units) gave 372 watts per pound of copper, and 1·31 volts per yard of coil.

FIG. 331.



PHŒNIX DYNAMO (1887 Wrought-iron Type).

The latter machines have upright single horse-shoe magnets, in some instances made of a single wrought-iron forging slotted out to form the two limbs, and bored, as shown in Fig. 331. The shaft is supported from two gun-metal bridge-pieces. There are generally no teeth on the armature-cores, which are made of plain washers to avoid cost of milling out the teeth.

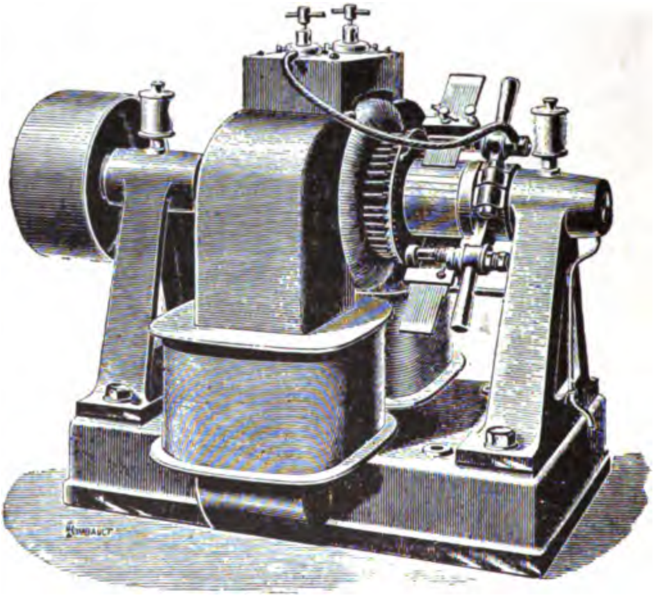
The following particulars of this machine have been furnished by the makers :—

The 25 kilowatt machine is designed for an output of 100 amperes at 250 volts pressure, when driven at 700 revolutions per minute. The total weight is 3136 lbs.; the useful output being 8 watts per pound of material. The external diameter of the armature core is 34·6 cm.; internal diameter of armature core, 20 cm.; length of armature core, 30 cm.; cross-section of magnets, 30 cm. by 20 cm.; nett sectional area of iron in armature, allowing for insulation, 193 sq. cm.; sectional area of iron in field, allowing for rounded corners, 612·7 sq. cm.; diameter of polar cavity, 37·5 cm. The armature is wound with 360 turns of 3·75 mm. square wire in two layers. The field is shunt-wound, each limb containing 3540 turns of 1·55 mm. wire, and the total resistance is 83 ohms. The radiating surface of both magnet limbs is 7740 sq. cm., and the energy used in exciting is 750 watts; the ratio of the cooling surface being therefore 10· 3 sq. cm. per watt.

From the above data we find that the total number of magnetic lines that cross the armature is about 6,200,000, and that the useful induction through the armature is 16,000, and the induction through the field 10,100 lines per sq. cm. The peripheral speed of the armature core is 2530 feet per minute, and the total length of conductor wound on the armature is 11,200 inches, being at the rate of 45 inches per volt in the external circuit. At a peripheral speed of 3000 feet (which is a fair average in modern belt-driven dynamos), 38 inches of armature conductor would produce 1 volt. In larger machines for heavy output of current, the makers have for six or seven years past used a stranded cable as conductor for the armature. This construction, which nearly all makers now follow, obviates eddy-currents which would arise in solid bars.

Fig. 332 shows an alternative design, in which the field-magnets are cast in one piece. This is not so powerful a machine for equal weight, but can be made of equal power as the wrought-iron machine at lower cost. In both machines there is no joint in the magnetic circuit, and the magnet coils are wound upon special bobbins of sheet-iron flanged with brass, slipped on over the cores. Fig. 271, p. 376, shows the construction of the commutator, and the manner in which the segments are insulated and secured from flying out of place.

FIG. 332.



PHŒNIX DYNAMO (1887 Type).

On Plate V. are given the drawings of one of these machines, giving 90 amperes at 105 volts at 1420 revolutions per minute. The constructional data of this dynamo and full calculations of the windings are given on p. 416 in the chapter on Designs. It will be noticed in this machine, which has cast-iron magnets, how small, relatively, is the section of iron in the armature. The same carcase, if wound differently, with many turns of fine wire, would serve as an arc-light machine, the magnets being for this purpose more highly saturated and a relatively greater weight of copper wound upon them.

In a large 4-pole Phœnix machine, cast-iron magnets are used, the armature core being formed by winding square iron wire on a gun-metal flanged cylinder.

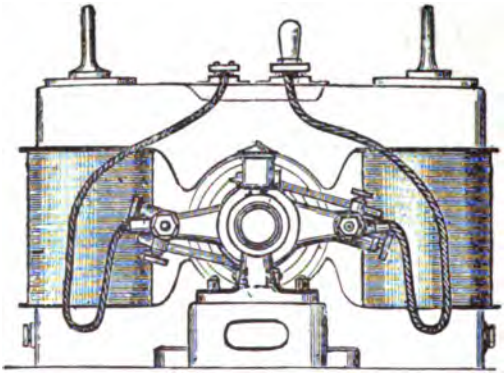
The same makers have produced arc-light dynamos to yield 10 amperes at pressures varying from 700 to 1500 volts. The following are the data of a seven-kilowatt arc-lighter, for 12 to 15 arc lamps:—

Armature core, 32·5 cm. external diameter, 22·9 cm. internal; axial length, 15 cm.; wound with 1872 turns of wire 1·2 mm. in diameter, in 48 sections of 39 turns each in three layers. Armature resistance, 3·448 ohms. Field-magnet coils, 2, of 954 turns each, in series; their total resistance, 4·541 ohms. The maximum induction in armature is 19,080, in field-magnet 10,800 lines per sq. cm.

"MANCHESTER" DYNAMO.

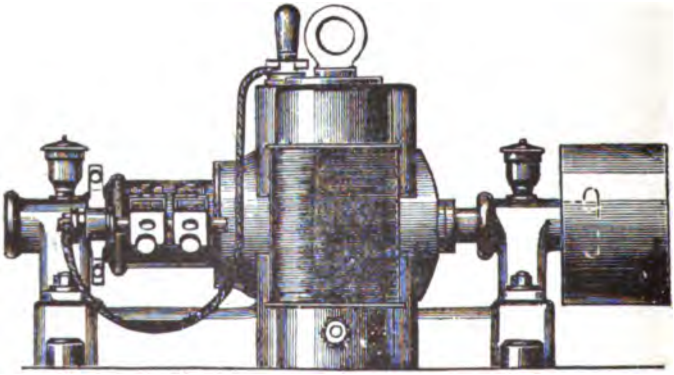
The field-magnet of this well-designed machine is shown in Figs. 333 and 334. It resembles earlier forms by McTighe and by Joel, but the wrought-iron cores are cylindrical and the cast-iron yokes very massive. It is constructed by Messrs. Mather and Platt, and was designed by Dr. Edward Hopkinson. The armature, designed by Dr. J. Hopkinson, F.R.S., and Dr. Edward Hopkinson, is a modified Gramme, with low resistance and careful ventilation. The collector is unusually substantial, and consists of 40 bars of toughened brass insulated with mica. It is usual in these machines so to shape the pole-pieces that there is a smaller clearance opposite the highest and lowest points of the armature: this concentrates the magnetic field and helps to prevent its distortion by the armature current. In a 24-unit machine (designed for 300 lamps) of this pattern the armature cores are 12 inches long and 12 inches in diameter, with 120 turns of wire. The resistances are: armature, 0·023 ohms; shunt, 19·36 ohms; series coil, 0·012 ohm. With a speed of 1050 revolutions per minute the current was 220 amperes, the machine being nearly self-regulating for 111 volts; its efficiency is 90·9 per cent.[1]

FIG. 333.



MATHER AND HOPKINSON'S DYNAMO (End Elevation).

FIG. 334.



MATHER AND HOPKINSON'S DYNAMO (Front Elevation).

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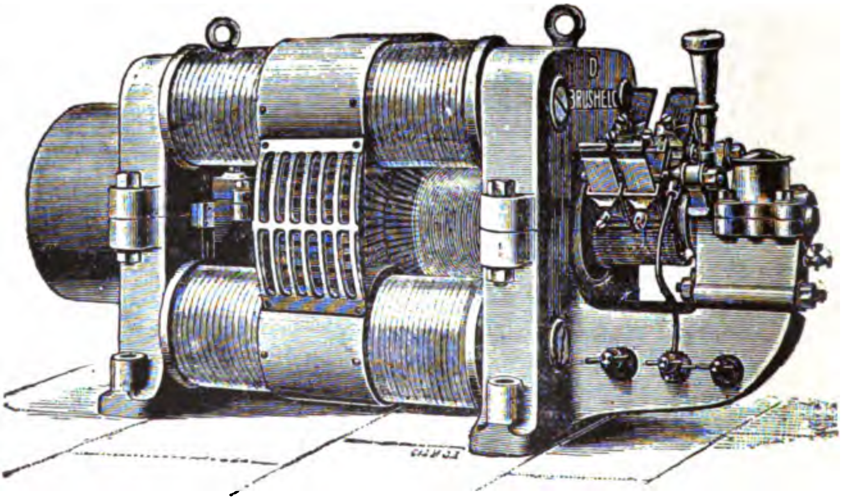
[1] One of these machines is very fully described in the paper by Drs. J. and E. Hopkinson in the *Phil. Trans.* for 1886.

"VICTORIA" (BRUSH CO.'S) DYNAMOS.

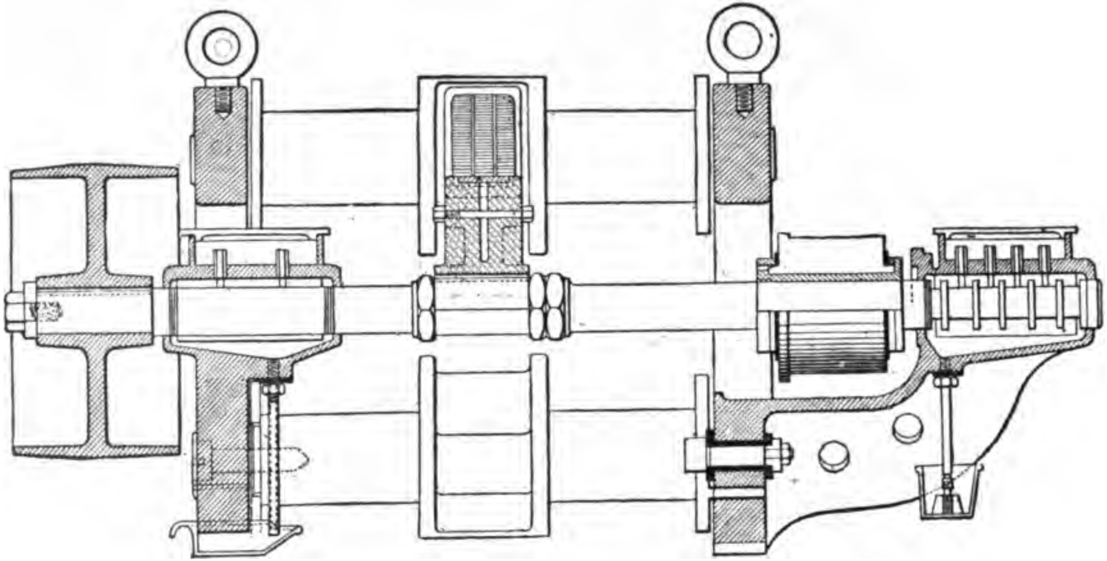
The Brush Electrical Engineering Co. has produced a dynamo of the flat-ring type, under the patents of Schuckert, Mordey, Wynne, and Sellon, to which the not very apt name of the "Victoria" dynamo has been given. There are two types of this dynamo, one having four, the other six poles arranged round the ring. The development of the Victoria machine from the original Schuckert machine commenced, under the auspices of the electricians of the Brush Company, with the discovery by Mr. Mordey, by the aid of his method of examining the distribution of potentials round collectors, that there was in the machine a point at a considerable distance in front of each brush, having the same potential as the brush, and that the whole of the portions of the armature between these equipotential points were useless, or worse than useless, as they were occupied only in producing an opposing electromotive-force. In some of the early Schuckert dynamos these useless portions occupied more than half of the armature. By reducing the size of the pole-pieces, space was found for a 4-pole field, the effect of the change being that, from the same ring as employed by Schuckert with a 2-pole field, the electrical output was doubled, without increase of speed. Great attention has been given to the form of the pole-pieces. These pole-pieces in the earlier Schuckert machines, consisted, as mentioned above, of hollow iron shoes or cases which occupied a large angular breadth along the circumference of the ring. Similar hollow polar extensions were long used in the Gülcher machines. By long extended experiments Mr. Mordey arrived at a narrower form of pole-piece, not covering more than 30° of angular breadth of the circumference of the armature, which completely obviated these effects. As will be seen from Fig. 335, which represents the 4-pole Victoria dynamo as now constructed, the pole-pieces, though they embrace the ring through its whole depth, from external to internal periphery, are not quite so narrow. This has been rendered possible by changes in the proportions of the dynamos, which have reduced the inductive effect of the armature. The pole-pieces are of cast iron shrunk upon the cylindrical cores of soft wrought iron which receive the coils. The armature of the Victoria dynamo has several times been modified, and its core is now made of almost square section. It is built up of charcoal iron tape, coiled upon a strong foundation ring, contact between successive layers being prevented by coiling paper between. Special pains have been taken throughout to ensure that there are no electric circuits made in the bolting together of these cores; each layer being insulated from the adjacent layers. Eddy-currents in the core are thus almost entirely obviated. The foundation ring and some of the inner convolutions of tape are slotted out to receive the gun-metal arms, of which there are two sets clamped together, one on either side. Fig. 336 shows this construction and the method of securing the ring to the shaft by lock-nuts. Square wire is used for winding the armature coils, and as they do not cover the entire

FIG. 335.



VICTORIA (SCHUCKERT-MORDEY) DYNAMO OF BRUSH ELECTRIC ENGINEERING CO.

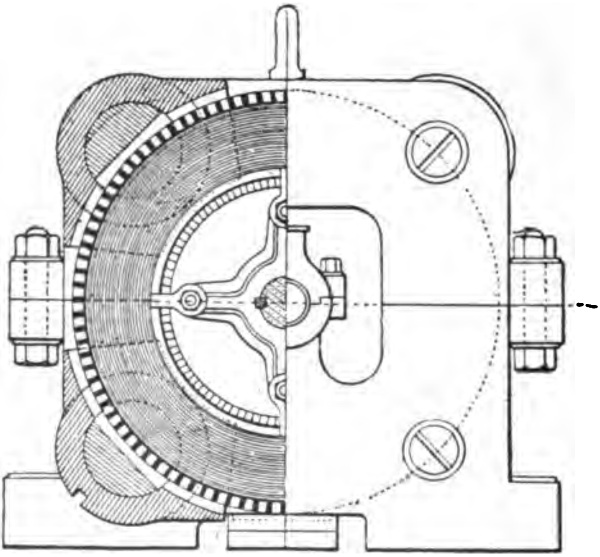
FIG. 336.



VICTORIA DYNAMO (showing Section and Method of Mounting the Ring).

external periphery of the armature core, there is ample ventilation. The winding is of one continuous wire, and the crossings are effected at the outer periphery. End-play is prevented by the use at one end of a deeply-grooved Babbitt-metal thrust-bearing. Formerly, in a 4-pole machine, four brushes were necessary—as in the Gülcher dynamo and the 4-pole Gramme. Mr. Mordey, as mentioned above, reduced the number to two, by the device of cross-connecting. Two brushes only are then necessary, and these are 90° apart.

FIG. 337.



VICTORIA DYNAMO (End View and Transverse Section).

The Victoria dynamo is usually compound-wound, having all the eight magnet-cores wound with main-circuit coils inside and shunt coils outside, the main-circuit coils being wound on slightly in excess of the amount needed to produce an exactly equal potential at all loads. In a "D^2" machine, wound for a potential of 60 volts, the following values were obtained:—Open circuit, 58 volts; 10 amperes, 58·5 volts; 20 amperes, 59 volts; 60 amperes, 59·7 volts; 90 amperes, 59·9 volts; 120 amperes, 60 volts. It will be seen that for small loads the potential drops a little; but it is under these circumstances that the engine speed usually rises slightly in practice, so that the constancy of the potential between the mains is somewhat better than the figures would show. In actual practice the regulation is perfect, because the over-compounding serves to compensate for the drop of volts in the mains. The author has opened the circuit of a Victoria dynamo which at the time was feeding 101 lamps, 100 being at a distance, one lamp attached to the terminals of the machine. On detaching the main wire from the terminal, the 100 lamps were suddenly extinguished. The solitary lamp on the machine did not even wink, and there was no flash at the brushes. The sparking was so slight it was impossible to tell whether the machine was on open circuit or whether it was doing full work. The lead was the same under all loads. The machine depicted in Fig. 335 weighs 1904 lbs., and has an output of 18,000 watts at 1000 revolutions per minute. Such machines are now guaranteed under tender to run at a commercial efficiency of 92 per cent.

A larger type of Victoria machine, having six poles alternately N. and S. set round the ring, has also been constructed by the Brush Company. As each segment of the collector is connected with those situated at 120° and 240° distance round the set, only two brushes are required. A figure of this machine was given in the previous edition of this work.

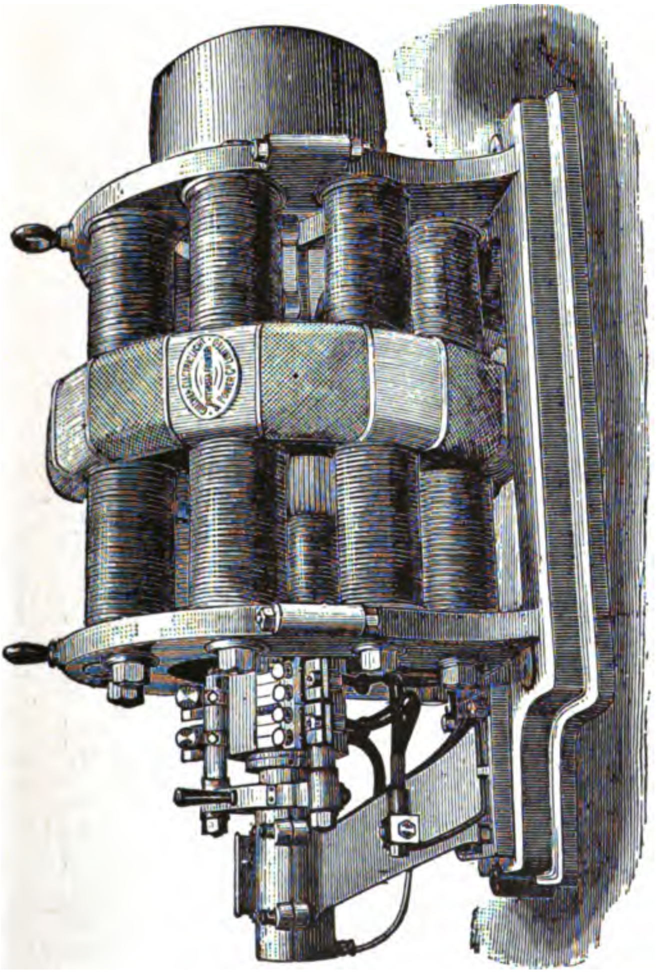
The advantage originally claimed for the flat-ring construction, that it allows less of the total length of wire to remain "idle" on the inner side of the ring, is rather imaginary than real, for the total resistance of the armature is but a small fraction of the whole resistance of the circuit; and it is possible to spread the field so as to make all parts of the wire active without any gain whatever, if by this spreading there is no increase on the whole in the total number of lines of force in the field. The real reasons in favour of multipolar flat-ring armatures appear to be the following:—First, their excellent ventilation; second, their freedom from liability to be injured by the flying out of the coils at high speeds; third, their low resistance, due to the fact that the separate sections are cross-connected, either at the brushes, or in the ring itself, in parallel. To these points may be added that, with an equal peripheral speed, the armature rotating between four poles undergoes twice as much induction as when rotating between two poles, since it cuts the lines of force twice as many times in the former case as in the latter.

GULCHER CO.'S DYNAMO.

In this machine as originally brought out, the ring core consisted of a number of flat washers of sheet-iron clamped together, rotating in a 4-pole field, and furnished with four collecting brushes at the commutator. There were four hollow, box-like pole-pieces of iron, cast upon wrought-iron cores, embracing a considerable angular breadth. In recent years this machine has been greatly improved by the engineers of the Gülcher Electric Lighting Company. They have followed the same line of progress as that pursued in the design of the Victoria dynamo. The lamination of the cores has been tangential instead of radial; the field-magnets have been made more powerful; the pole-pieces have been reduced in breadth; and the number of the brushes has been reduced by cross-connexions in the armature to two. Fig. 338 shows an 8-pole type of machine, which has been largely used by this company both for lighting and for electro-deposition. In this cut the armature is covered from sight by guards of perforated metal. These machines have been made in all sizes up to 32 units.

The latest type of Gülcher dynamo is depicted in Figs. 339 and 340. In Fig. 339 the lower half shows a section in the vertical plane along the line A B, whilst the upper half represents a section in the oblique plane of the line A C, so as to show the true section of the polar portions. The drawings relate to a 4-pole 10-unit machine, designed to give 185 amperes, at 65 volts, at a speed of 900 revolutions per minute. The dimensions and details of construction are as follows: The end-yoke frames and the pole-shoes are of cast iron. The magnet-cores, 4 inches in diameter and 5 inches long, are screwed into the pole-shoes, and their other ends are turned down and fitted with circular nuts so as to secure a large contact-surface with the yokes. The armature is built up of rectangular charcoal iron wire wound upon a gun-metal pulley, forming a core of nearly square section. This is over-wound with insulated copper wire in 80 sections of four turns

FIG. 338.



GULCHER DYNAMO.

each, the wire being rectangular, ·12 × ·85 inch, lying in a single layer outside and in two layers inside the ring, which

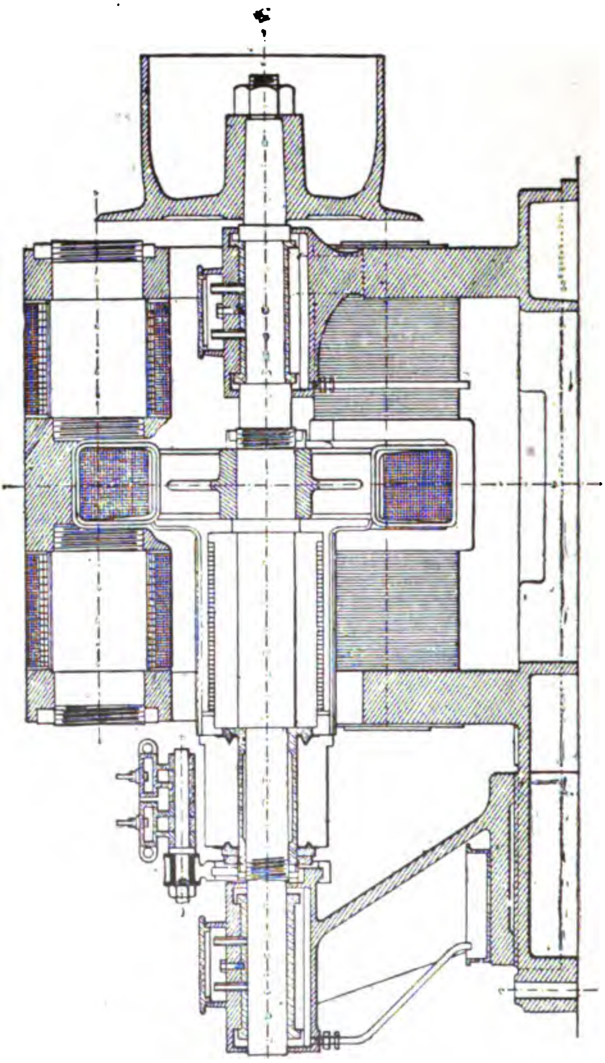
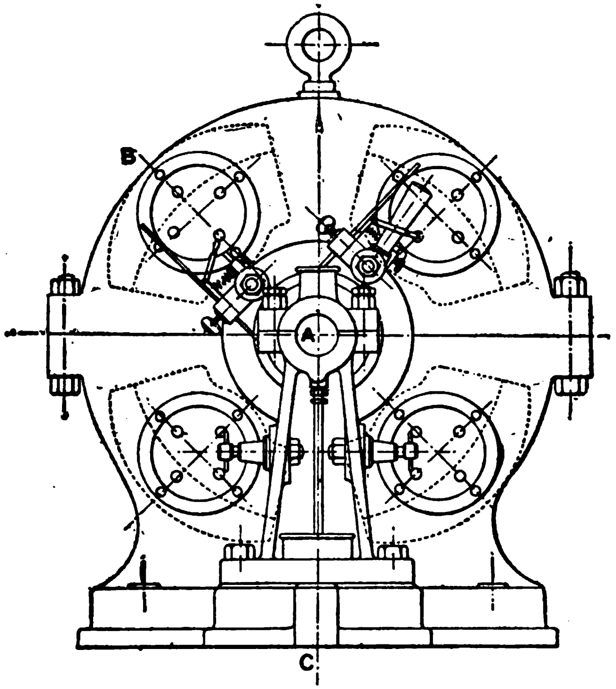


Fig. 339.

Gulcher Co's Dynamo (1888).

when finished has a square 3-inch section and is 15 inches in diameter. The resistance is ·025 ohm, and the weight of copper is 18½ lbs. The commutator has 80 segments of hard-drawn copper insulated with mica ·75 mm. thick, clamped together, with proper insulation, over a gun-metal sleeve. The requisite cross-connexions between the opposite bars of the commutator are effected by a series of insulated copper rings, supported on a wooden sleeve placed between the armature and the commutator. Each ring has two lugs at opposite sides, these lugs being soldered to the wires that run from the ring windings to oppositely situated bars of the commutator. This machine is compound-wound, the windings being as follows :—Shunt coils of wire ·075 inch diameter, 8 layers of 44 turns each in each coil; total weight of the 8 shunt coils, 77 lbs.; total resistance joined in series, 7·805 ohms. Series

Fig. 840.



Gulcher Co.'s Dynamo (End View).

coils of rectangular wire, ·13 × ·26 inch, in 2 layers of 14 turns each on each core; total weight of 8 series coils, 38 lbs.; total joint resistance of series coils, ·005 ohm.

RANKIN KENNEDY'S DYNAMOS.

This inventor has given the name of *iron-clad* to those forms of dynamo in which the field-magnets enclose the exciting coils.[1] One of these forms of field-magnet, which is discussed on p. 200, has four poles, two of them being salient poles protruding directly through the exciting coils on either side of the armature, the other two poles being consequent poles formed at the middle-points of the upper and lower portions of the iron framework, which here are bored away to form polar surfaces. Another form[2] of Kennedy's, having one coil only, resembles Fig. 121.

SIEMENS' DYNAMOS.

These originated with Messrs. Siemens and Halske of Berlin, who have manufactured many different forms. In recent years there has been some divergence between the types followed in Berlin and those produced by the London firm of Siemens Bros. Until the last year or two the characteristic feature in all forms was the drum armature; but the largest machines are now made with rings. In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. In all the modern drums iron core-disks are now used. The various modes of winding are described in Chapter XIII.

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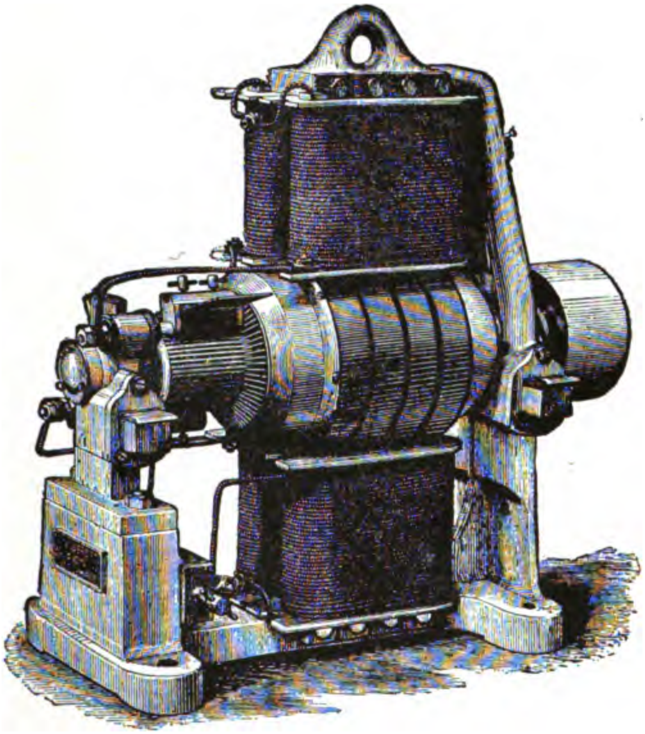
[1] An earlier type of "iron-clad" dynamo by the same inventor is described in *Industries*, i. 137, 1886.

[2] See data given by Jamieson in 1889 to Institution of Engineers and Ship-builders in Scotland, printed in *The Electrician*, March 1, 1889.

pp. 361 to 364, and their theory on pp. 318 to 326. The old horizontal pattern of Siemens' dynamo is depicted in Fig. 8, p. 16. This was followed about 1880 by the vertical form shown in Fig. 341. The field-magnets here consist of forged arched bars of wrought iron, with double magnetic circuit, having consequent poles right and left of the armature. The coils are wound on flat brass frames slipped over the cores. In some of the machines provision is made for ventilation by leaving an air-space between the brass frames and the cores. About 1882 various ways of compound-winding were tried,[1]

FIG. 341.



SIEMENS' DYNAMO (Vertical Pattern).

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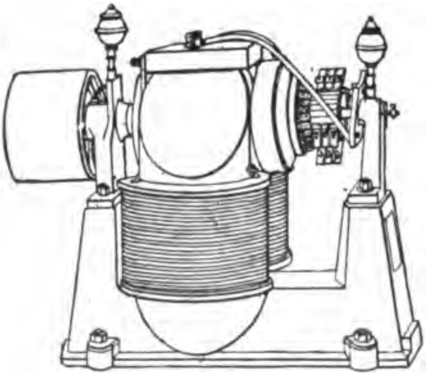
[1] See series of papers in the *Elektrotechnische Zeitschrift*, March–June, 1885, by Dr. O. Frölich.

in some of which the series and shunt-coils were wound on the same cores, and in others on different limbs, the usual practice being to wind the series coils outside the shunt windings.

Some very large machines of the vertical pattern, but with many improvements in detail, including three 112-unit compound-wound dynamos, "B 13" pattern, were used at the Inventions Exhibition of 1885. Each of these was capable of yielding 450 amperes at a potential of 250 volts, making an output of 112,500 watts, when running at 300 revolutions per minute only. The armatures were wound with flat strip-copper.

In 1886 Messrs. Siemens and Halske, after trying some intermediate forms (depicted on pp. 159 and 160 of the second edition of this book), adopted the over-type depicted in Fig. 342. The field-magnet of this machine consists of a single very massive casting, over which the exciting coils are slipped.

FIG. 342.

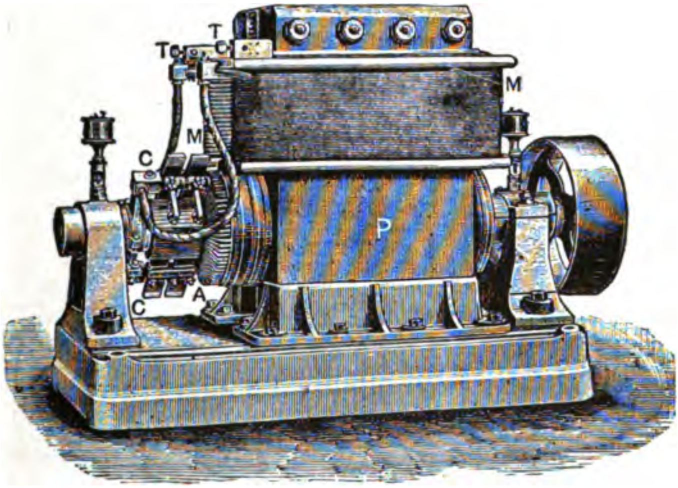


SIEMENS' DYNAMO (Berlin type of 1886).

The commutators of these machines are massive, and consist of iron bars attached by screws at one end only so as to be replaceable, and insulated by air-gaps. The brushes are adjustable; and they are trimmed with broad oblique ends so as to touch at least two collector-bars at once. The form of brush-holder used in all Siemens' and Halske's dynamos is shown in Fig. 279, p. 385. Dynamos of this type are made for outputs from 1½ to 80 kilowatts, the largest having a peripheral speed of 14 meters per second.

The London firm has constructed much larger drum machines for central-station lighting, mainly of the undertype. Fig. 343 represents one of these machines, compound-wound, with the series winding on one limb only. At the Naval Exhibition of 1891 were shown three fine dynamos of 180 kilowatts each, at the slow speed of 350 revolutions per minute. The armature is 24 inches in diameter, 36 inches long, and weighs 2·4 tons; and the entire dynamo weighs 13·6 tons. The armature conductors are stranded bars; the commutator of hard-drawn copper, insulated with mica, with 144 segments, 9 inches long, with three pairs of brushes to collect the 1500 amperes. The rocker is provided with worm-wheel to adjust the proper lead. There are two independent circuits of 72 turns each, which are put in parallel with one another by the brushes, which are made broad enough to overlap three consecutive bars of the commutator.

FIG. 343.



SIEMENS' DYNAMO (London type of 1890).

Towards the end of 1886 a form of multipolar ring machine, with ring external to the field-magnets, was brought out almost simultaneously by Messrs. Ganz of Buda-Pesth, Messrs. Fein of Stuttgart, and by Messrs. Siemens and Halske of Berlin.[1] It will be sufficient to describe the machines of the latter firm.

The field-magnet, as shown in Figs. 344, 345, is stationary and internal to the ring. In the small machines this consists of a substantial cross-shaped mass of cast iron, through the centre of which passes the driving-shaft. The four poles, after receiving the exciting coils, are furnished with polar expansions, which approach close to the inside of the ring. The ring itself is made up of thin iron washers bolted together, and supported on one side by a brass spider keyed to the shaft. A machine of this type, weighing 2660 lbs., with an output of 25,000 watts at 480 revolutions per minute, had a ring of 20 cm. broad and of 64 cm. internal diameter. The advantages of this type are the ease of repair, the immense cooling surface of the armature, and the non-necessity of applying binding-wires. In the first of these machines the commutator was hollow and consisted of stout bars of iron, with air insulation. In the larger machines there is no separate commutator, the brushes being applied against the exterior of the ring itself.

Large ring machines of this type have been supplied to the principal central stations[2] in Berlin and other cities in Germany. In Plate XI. are given drawings of some of these machines, the largest hitherto made, from the station at Spandauerstrasse, Berlin, the scale being 1 : 80. The dynamos are mounted in pairs on the ends of the main shaft of an enormous compound condensing-engine of marine type, by Kerchove & Co. of Ghent, having 5 feet 5 inches stroke, the diameters of the cylinders being respectively 2 feet 6 inches and 4 feet 5 inches, giving 1180 indicated HP., or 1000 actual HP., at 75 revolutions per minute. Each dynamo is capable of giving 2000 amperes at 140 volts, at only 60 revolutions per minute. The field-magnet has 10 salient poles, with

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[1] For further information about the various machines of this type see *Elektrotechnische Zeitschrift* for April and May, 1887; *La Lumiere Electrique*, xxiv. 182, 1887; *Centralblatt für Elektrotechnik*, ix. 186, 410, and 581, 1887.

[2] See *Die Berliner Elektricitats-Werke*, by Arthur Wilke, Berlin, 1891; also articles in *Elektrotechnische Zeitschrift*, x. 479, 563, 1889; xi. 53, 1890; *La Lumiere Electrique*, xxxvi. 441, 1890; and *Electrical World*, xvii. 14, 1891.

FIG. 345.

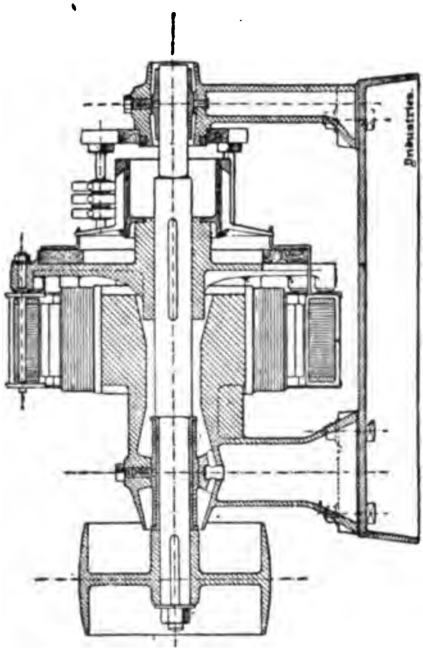
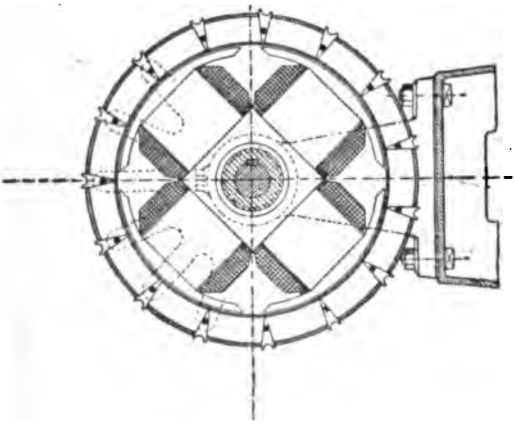


FIG. 344.



SIEMENS AND HALSKE'S RING DYNAMO (INTERNAL-POLE MACHINE).

rectangular cores fixed to an annular yoke-ring, which is carried in a U-shaped support on the bearing. It is shown in section on the right-hand end of Fig. 1, Plate XI. The exciting coils are all joined together in series, and connected in shunt to the armature. The armature is built of core rings mounted on insulated arms, which project from a bronze star-wheel, thus overhanging the field-magnet. Fig. 256, p. 360, shows the detail of construction. The winding, as that figure shows, consists exteriorly of straight copper bars, united by other pieces of bent form which pass through the inside of the ring from the end of one straight bar to the beginning of the next, thus constituting a spiral and endless winding. The collecting brushes trail against the exterior bars, as shown in the perspective view, Plate XI., Fig. 3. The external diameter of the armature, which thus serves as commutator, is 9 feet. The brush-holders *e* in Fig. 1, Plate XI., are mounted on a stellate rocker *g*, by which they can all be simultaneously shifted forward or back by the toothed gear shown in Fig. 3, Plate XI. The brushes can also be all raised simultaneously out of contact by a lever *f*, united by connecting rods to another star-piece. Their construction is that shown in Fig. 279, p. 385. At the Spandauerstrasse station are four such engines of 1000 nominal HP., each driving two dynamos, supplying in total 40,000 to 50,000 lamps. At the Markgrafenstrasse station are four single steam dynamos of 400 HP. each. At the Mauerstrasse station are three double steam dynamos of 1000 HP., and two single of 400 HP. each. At the new Schiffbaudamm station are six double steam dynamos of 1000 HP. each.

At the Frankfort Exhibition of 1891 a similar dynamo was shown[1] direct-driven from a triple condensing engine by Kuhn of Stuttgart, of 300 kilowatt capacity, giving 2200 amperes at 150 volts at 65 revolutions per minute. The magnet of this dynamo had 10 poles, being 272 cm. in diameter. The external diameter of the ring was 310 cm., wound with 810 convolutions, each bar being about 1 cm. wide, with paper insulation. There were 10 sets of brushes, three in each set, each brush being 4·5 cm. wide, of rectangular copper wire. The star-piece carrying the overhung armature was of cast-iron with 30 arms, supporting the core-disks by means of 30 insulated steel bolts. To collect the currents the five positive brush-sets are united together, and the five negatives are also connected together; the currents being conveyed to the mains by flexible cables. At a speed of 100 revolutions per minute this machine reaches an output of 600 kilowatts.

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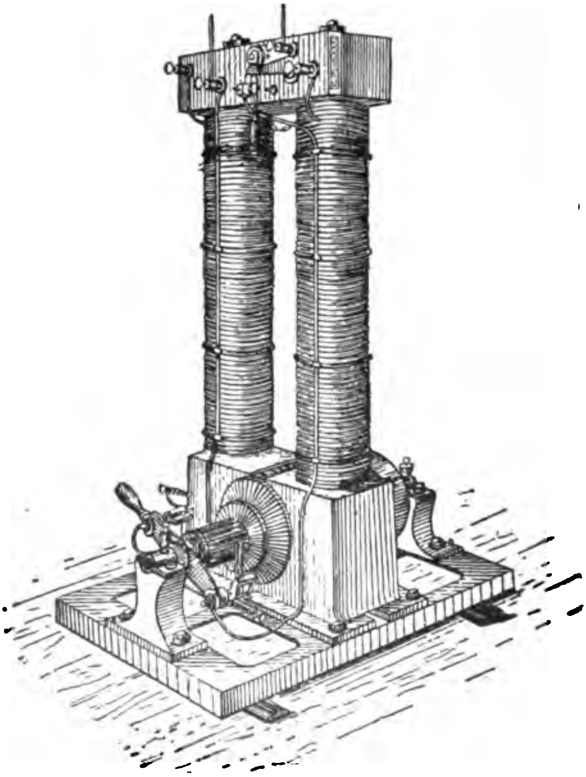
[1] See description by Esson in *Electrical Review*, xxix. 342, 1891.

EDISON DYNAMOS.

In 1879, after proposing a strange sort of machine as generator, in which inductive coils were waved to and fro at the end of the prongs of a gigantic tuning-fork, Mr. Edison, with the assistance of Mr. Upton, designed the machine which is depicted in Fig. 346. It has a drum armature rotating between heavy pole-pieces excited by a very long magnet with tall columnar limbs. The "Z" pattern of machine was capable of lighting 30 Edison lamps. In the Edison armatures the number of sections of the winding is an odd number.

In the first machines there were seven paths, as shown in Fig. 208 (p. 319), taken from Edison's British Patent Specification. In his large "steam dynamo" of 1881 the number of sections was 49. One consequence of this peculiarity of structure is, that if the brushes are set diametrically opposite to one another, one will touch the middle of a bar of the collector at the instant when the other slides from bar to bar. In Edison's larger dynamos the armature is made of bars of copper. The mode of connecting the ends by means of copper washers is described on p. 365. For larger machines two or three tall field-magnets like Fig. 346. were assembled side by side, over an armature of double or triple length. An Edison 60-light "Z" machine of the older pattern, tested by the Committee of the Munich Exhibition, was found to give an efficiency, which, if measured by the ratio of external electric work to total electric work, exceeded 87 per cent.; but its commercial efficiency—the ratio of external electric work to mechanical energy imparted at the belt—was only, at the most, 58·7 per cent. This was due to the production of wasteful eddy-currents in the bolts which held together the armature and other masses of metal. The "Jumbo" steam dynamos were even less efficient, and required a 4 HP. fan to be attached to the armature shaft to keep them cool by a forced draught of air.

FIG. 346.

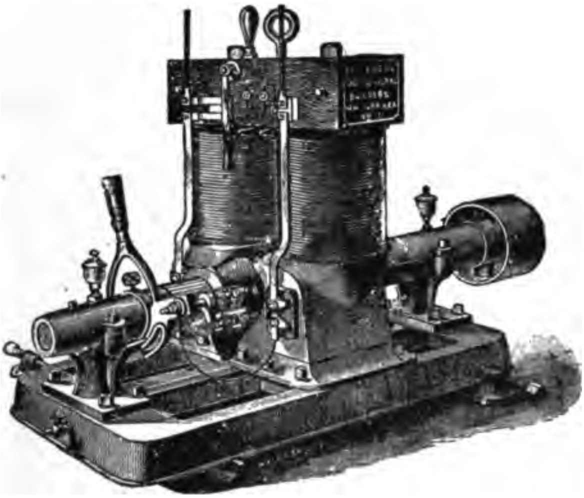


EDISON DYNAMO, "Z" PATTERN (1881).

Dr. J. Hopkinson's efforts to improve this machine resulted, as detailed below, in a better design.

The field-magnets of all the larger machines turned out by Edison prior to 1884 had a number of long iron columns as cores to receive the coils. Since that date the more compact arrangement of a single magnetic circuit with short stout magnets has been adopted by the Edison companies on both sides of the Atlantic. The usual form (type of 1888,) of Edison dynamo, as used in the States, is depicted in Fig. 347.

FIG. 347.



EDISON DYNAMO (1888 Type).

The field-magnets are of cast iron, with a massive yoke, and stand upon a high footstep of zinc to diminish magnetic leakage through the bed-plate. These machines are shunt-wound, and are intended for incandescent lighting work. The bearings are longer and the mechanical arrangements in every way superior to those of the older machines.

At the Paris Exhibition of 1889 were a number of dynamos built by the Edison Machine Company, of Schenectady, ranging from a small 2½ kilowatt machine, 15 inches high, to one of 150 kilowatts, 102 inches high. Figs. 1 to 4, Plate VII., depict two of these machines, Figs. 1 and 2 are drawings of the largest machine. This dynamo is capable of supplying 1250 amperes at 140 volts, when running at 250 revolutions per minute. It has a 41-part commutator and an

82-bar armature. There are six brushes in each set, each 1·88 inches wide and about 0·62 inch thick. Its weight is 12½ tons.

Some particulars published in 1890 by M. Minet[1] concerning some of these dynamos show that the speeds vary from 2000 revolutions per minute in the 2½ kilowatt machine up to 800 in a 45 kilowatt machine. The peripheral speeds varied from 12·5 to 14 metres per second. Mean value of B in gap space from 3200 to 4100. The gross efficiency of the larger machines was about 95·6 per cent.; the electrical efficiency 93·8; the net efficiency about 89·7 per cent.

Since returning from Europe in 1889 Mr. Edison has designed some larger multipolar dynamos direct-driven from vertical triple-expansion engines. Plate XIII.[2] shows two 100 kilowatt dynamos fixed at the ends of the crank-shaft, precisely as with the larger Berlin dynamos. The engine is of 300 HP. at 176 revolutions per minute. The field-magnets are external, with eight consequent poles; and the armature is ring-wound. The conductors are made up of straight pieces on one face of the ring joined by U-shaped pieces into a continuous winding. The straight pieces serve also as commutator against which the eight sets of brushes press. There are 944 convolutions; and as alternate sets of brushes are connected together, there are really eight rows of 116 turns each in parallel. Each dynamo gives 666 amperes at 150 volts. The armature resistance is 0·006 ohm; that of the field-coils 8·45 ohms.

A smaller size of machine of the same type is shown in Figs. 348, 349, each of the two dynamos being of 75 kilowatts capacity. The new central station in New York will be equipped with 14 such machines, each with two 400 kilowatt dynamos. It will therefore be like the European kind of central station, and quite unlike the usual American central station, in which the most conspicuous feature is leather, a large number of small dynamos being driven by belts from countershafts.

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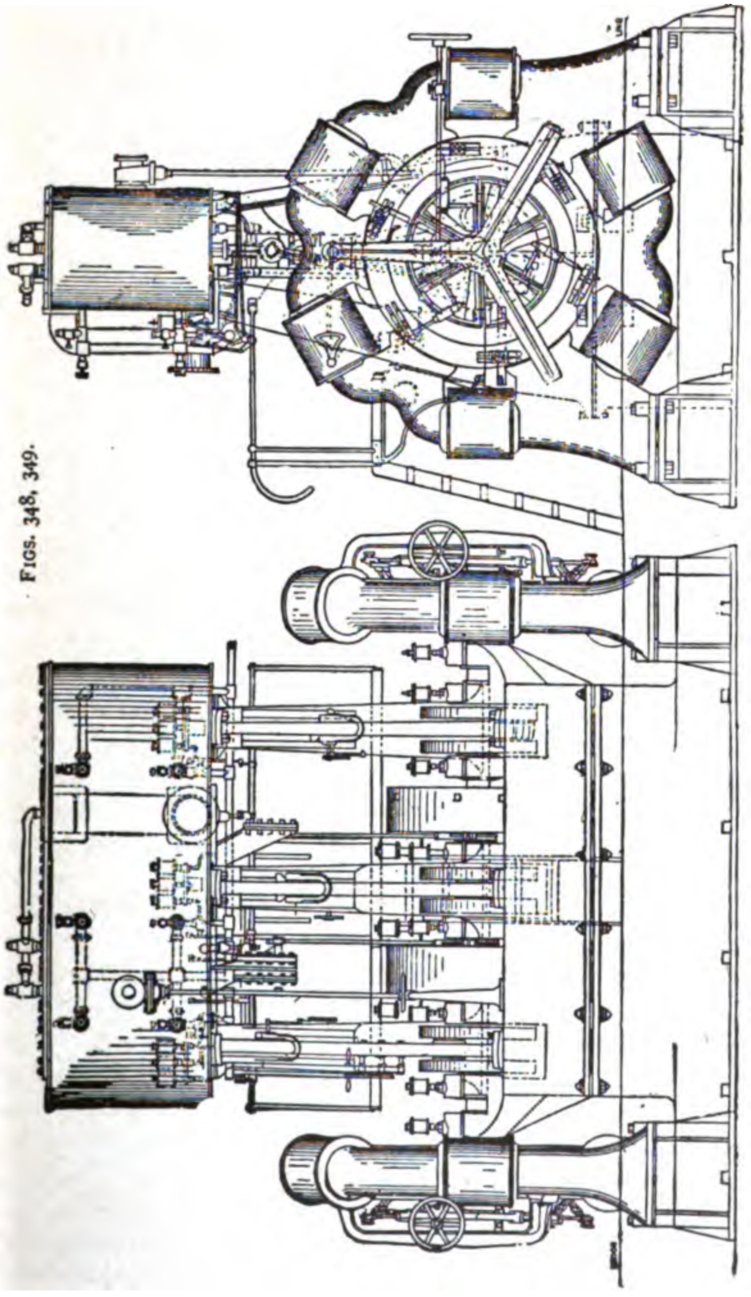
[1] *La Lumière Electrique*, xxxv. 401, 1890.

[2] See *Electrical Engineer* (N. Y.), xi. 480, 1891; by the courtesy of the editors of which journal the use of Plate XIII. is permitted.

FIGS. 348, 349.

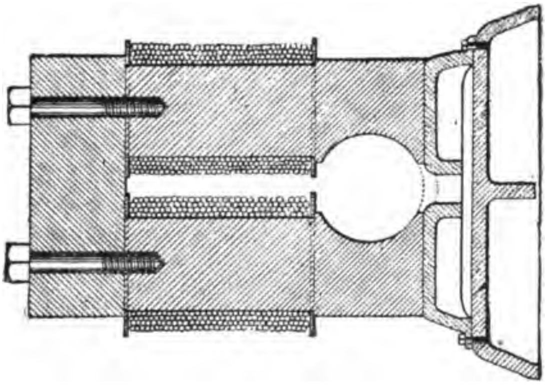


EDISON GENERAL ELECTRIC CO.'S MULTIPOLAR DYNAMOS.

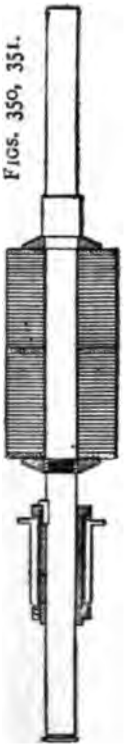
EDISON-HOPKINSON DYNAMOS.

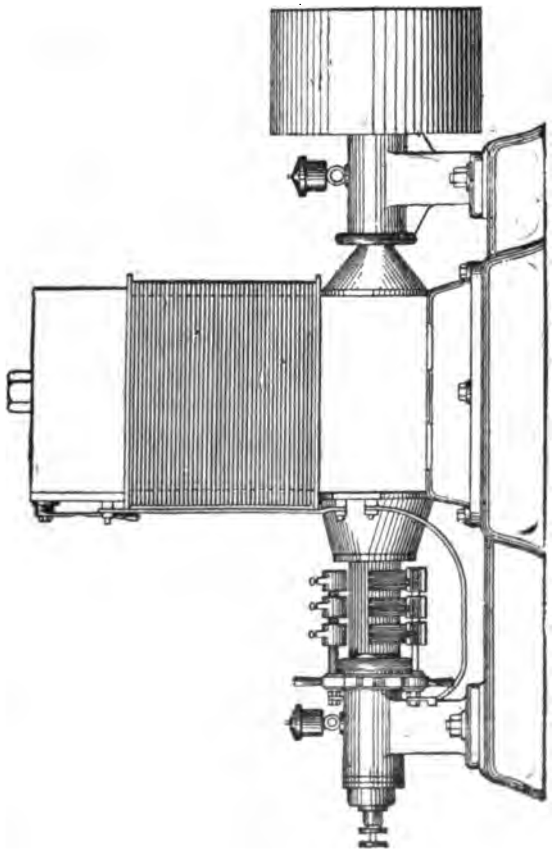
The Edison dynamo has received very material improvements at the hands of Dr. John Hopkinson. Some of these improvements relate to the field-magnet; others to the armature. Dr. Hopkinson, in the first place, abolished the use of the multiple field-magnets, which in Edison's original "L," "K," and "E" machines were united to common pole-pieces; and instead of using two, three, or more round pillars of iron, each separately wound, he puts an equal mass of iron into one single solid piece of much greater area of cross-section and somewhat shorter length. One such iron mass, usually oblong in cross-section, is attached solidly to each pole-piece, and the two are united at the top by a still heavier yoke of iron. The machines have, consequently, a more squat and compact appearance than before (Figs. 351 and 352). Dr. Hopkinson also introduced the improvement of winding the magnets with a copper wire of square section, wrapped in insulating tape. This wire packs more closely round the iron cores than an ordinary round wire. In the armature the following change has been made:—The iron core in the older Edison machines was made of thin iron disks, separated by paper, slipped on over a sleeve of *lignum vitæ*, and held together by six longitudinal bolts passing through holes in the core plates, and secured by nuts to end-plates. These bolts are now removed, and the iron plates are held together by great washers, running upon screws cut on the axle of the armature. The size of the central hole in the plates has been diminished, thus getting into the interior more iron, and providing a greater cross-section for the magnetic induction. By these improvements, a machine occupying the same ground space, and of about the same weight as one of the older "L" 150-light machines, was made capable of supplying 250 lights, the economic coefficient being at the same time higher. In the new 250-light machine, the diameter of the armature is 10 inches, its resistance (cold) is 0·02 ohm; that of the magnets is 17 ohms. The magnetization curve of the machine shows that even when doing full

FIG. 352.



FIGS. 350, 351.





EDISON-HOPKINSON DYNAMO: ELEVATION, SECTION, AND SECTION OF ARMATURE.

duty, the field-magnets are far from being saturated. It will be remarked that, in the older construction, the bolts and their attached end-plates furnished a circuit in which idle currents were constantly running wastefully round, with consequent heating and loss.

A remarkably complete account of one of these dynamos, constructed by Messrs. Mather and Platt, was published in 1886.[1] As this machine is often referred to in the theoretical chapters of this book, a detailed account of it is important. Its design may be gathered from Figs. 350, 351, and 352.

The machine described is intended for a normal output of 320 amperes at a pressure of 105 volts, running at 750 revolutions per minute. The field-magnet consists of two limbs connected by a yoke of rectangular section. Each limb, together with its pole-piece, is formed of a single forging. The wrought iron used for these and the yoke is of annealed hammered scrap; the magnetic properties being those described in Chapter VI. The section of the limbs is nearly rectangular, with rounded corners. The yoke is bolted to the limbs, the joints being well surfaced. The bed-plate is of iron, a zinc base 12·7 cm. high being interposed. The armature core is built up of about 1000 thin plates of soft wrought iron, insulated from the shaft, and separated by paper from one another. They are held between two end-plates, one of which is secured by a washer shrunk on the shaft, and the other by a screw-nut and lock-nut.

The following are the dimensions of the iron parts:—Diameter of armature core, 25·4 cm.; of internal hole, 7·62 cm.; of shaft, 6·98 cm.; length of core, 50·8 cm. Length of field-magnet limb, 45·7 cm.; breadth, 22·1 cm.; width (parallel to shaft), 44·45 cm. Length of yoke, 61·6 cm.; width, 48·3 cm.; depth, 28·2 cm. Diameter of bore of field-magnets, 27·5 cm.; depth of pole-piece, 25·4 cm.; width (parallel to shaft), 48·3 cm.; width between pole-pieces, 12·7 cm. Area of section of iron in armature core, 810 sq. cm. Angle subtended by bored face of pole-pieces, 129°. Actual area of pole-piece, 1513 sq. cm.; effective area, 1600 sq. cm. Thickness of gap-space, 1·5 cm. Area of section of limbs, 980 sq. cm.; ditto of yoke, 1120 sq. cm.

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[1] See paper on *Dynamo-electric Machinery*, by Drs. J. and E. Hopkinson, in the *Philosophical Transactions* for 1886, Part I. This most valuable paper was reprinted, but without the plates, in the *Electrical Review*, xviii. 1886. It was also printed in the *Electrician*, xviii. 39, 63, 86, and 175, in issues of Nov. 19th and 26th, and Dec. 3rd and 31st, 1886, where the figures of the plates are printed in the text.

The windings are as follow:—Magnetizing coils, 11 layers on each limb of copper wire, 2·418 mm. diameter. Total convolutions, 3260; total length, 4570 metres. Armature, 40 convolutions in two layers of 20 convolutions of stranded copper wire, consisting of 16 strands of wire 1·753 mm. diameter. Resistance (at 13·5° C.): field-magnet, 16·93 ohms; armature, 0·009947 ohm. Normal magnetizing current, 6 amperes. Commutator, 40 copper bars insulated with mica.

Recent tests with Edison-Hopkinson dynamos constructed by Messrs. Mather and Platt, of Manchester, show that they have an economic coefficient of over 95 per cent., and an actual commercial efficiency of over 93 per cent. These machines have usually from two to five separate brushes at either side, capable of separate removal, so that they may be trimmed without stopping the machine. In order to bring the neutral points of the commutator to convenient positions right and left, the connecting pieces which join the commutator bars to the armature windings are carried spirally through about 90°. The makers of these machines have modified in detail the winding of the armatures,[1] enabling them to use copper bars instead of stranded wire. They shape the pole-pieces to diminish distortion of field, and connect the armature bars across the ends of the armature by spiral connectors in two layers, like those used in Siemens' electroplating dynamos.

Figs. 353 and 354 depict the large 225 kilowatt dynamos built by Messrs. Mather and Platt for the South London Electric Railway. They are further shown in Plate XX. They have a maximum output of 450 amperes at 500 volts when running at 500 revolutions per minute. The limbs and yoke are of wrought iron, the polar masses of cast iron. The armature conductors are copper bars, and the resistance from brush to brush is 0·017 ohm. That of the shunt coil is 96 ohms, of the series coil 0·015 ohm. The compound winding is not, however, of much service for such rapidly varying loads as occur in railway work, for with such massive magnets

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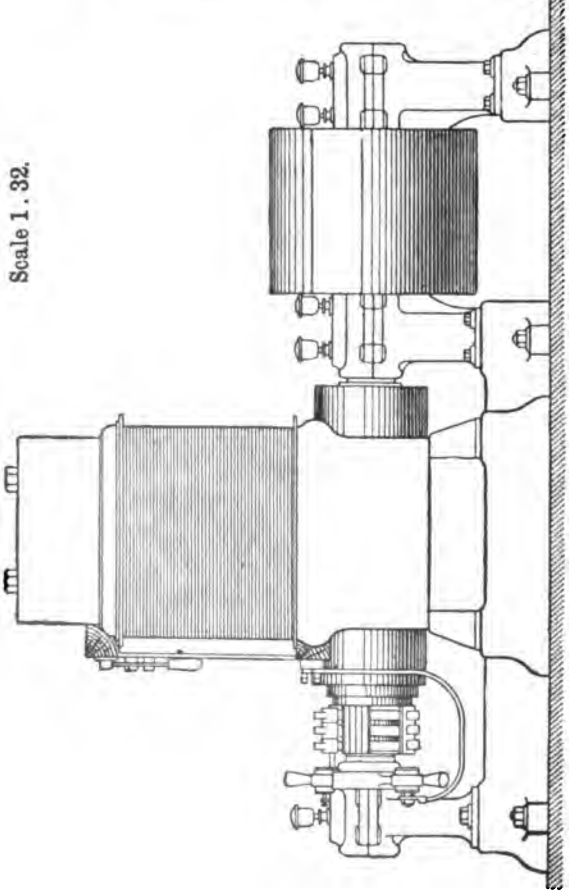
[1] See *Industries*, ii. 549, 1887; and Specification of Patent, 4884 of 1886.

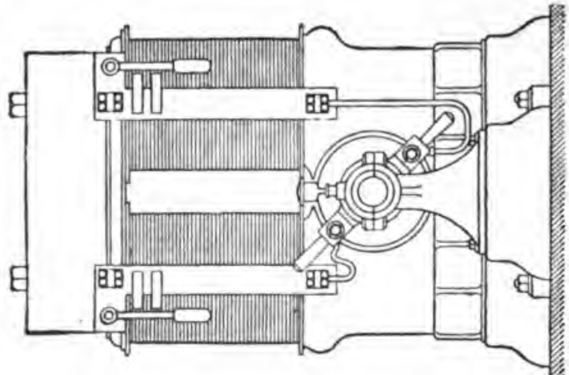
Fig. 353.



400 HP.

Scale 1 . 32.

Fig. 354.



Edison-Hopkinson Generators at City and South London Electric Railway.

changes of magnetism cannot take place rapidly enough. The weight of magnets and pole-pieces is 8·5 tons, that of the yoke 3·05 tons, of the armature 2·85 tons; whilst each complete machine with its bed-plate weighs 17 tons.

Some efficiency tests of a 53 kilowatt compound-wound Edison-Hopkinson dynamo direct-driven at 430 revolutions per minute by a Willans' engine have been published.[1] Indicated horse-power absorbed 85·3; output 475 amperes at 110 volts, or 52·2 kilowatts, or 70·0 horse-power; making a net efficiency of 83·3 per cent. The electrical efficiency was actually 96 per cent., the electrical losses being only 3 per cent., whilst 10 per cent. was lost in friction in engine and dynamo.

SCHUCKERT'S DYNAMOS.

The armature of the original Schuckert machine was a flat ring, the core of which was built up of a number of thin iron disks. The winding was identical with that of a Gramme machine, and the field-magnets resembled, in general, those of the typical Gramme. The ring was almost entirely enclosed between wide pole-pieces, each of which covered nearly half the ring. The ordinary pattern of machine is shown in Fig. 355, which shows how the frame admits of removing the armature. In recent years Messrs. Schuckert and Co. (of Nürnberg) have brought out many modified types of machines, but all having the flat-ring armature. The cores are now made of iron tape insulated with paper, coiled upon a brass foundation ring. Only the small sizes are made with two poles, all above 12 kilowatts being multipolar. As is the case with most German dynamos, the field-magnets are of cast-iron, the commutator bars are insulated with paper, and the wires secured to them by screws. At the Frankfort Exhibition of 1891 a large number of these machines were shown,[2] the finest of them being a large direct-driven multipolar of a certain capacity of 230 kilowatts, giving 1000 amperes at 230 watts, and taking 320 HP. at 160 revolutions

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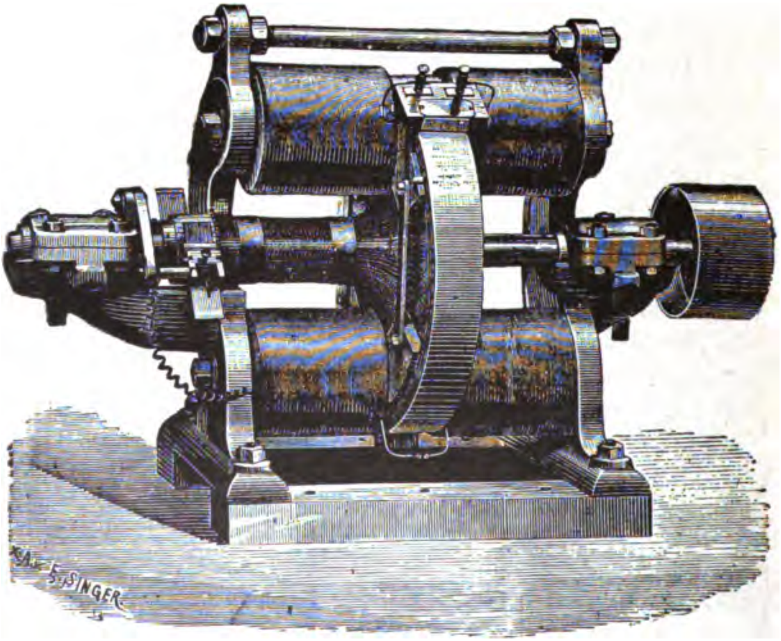
[1] *The Electrician*, xxv. 707, 1890.

[2] See article by Esson in *Electrical Review*, xxix. 526,1891.

per minute. This machine, Plate XII., stands about 8 feet above the ground, into which it sinks nearly 3 feet. The external diameter of the ring is 240 cm., wound with 1120 turns of braided stranded wire: the cross-section of iron in it being 680 sq. cm. The commutator is 150 cm. in diameter with 560 segments, cross-connected, so as to reduce the number of brushes. The resistance of the armature is 0·006 ohm; that of the magnet winding 7·4 ohms. There are 14 poles, and the armature winding is grouped in 14 rows of 80 turns each, all in parallel. The magnet poles project inwards from an external cast-iron case, divided horizontally. A thrust-bearing is provided to limit end-play, and this is carried on an outer bracket. There are four brush-holders, two positive and two negative, each carrying three brushes, each 5 cm. in

Fig. 355.



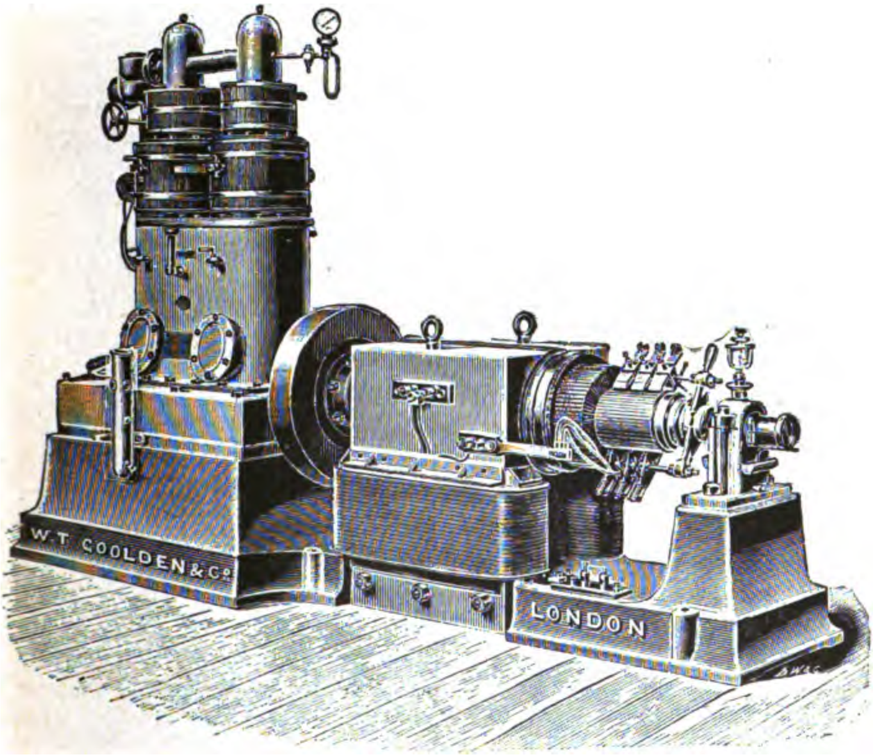
Schuckert's Dynamo, with Flat-ring Armature.

width, making a total width of 30 cm. for collecting 1000 amperes. A still larger machine with 16 poles is at work in the central station at Düsseldorf.

GOOLDEN'S DYNAMOS.

Excellent dynamos have long been manufactured by the firm of W. T. Goolden & Co. The calculation of their design by Mr. Ravenshaw has already been alluded to: their swivel bearings were noted on p. 394, their screw-fed brushes on p. 384, and their driving-horns of fibre on p. 355. In their larger dynamos bar armatures are employed, having rectan-

FIG. 356.



GOOLDEN DYNAMO AND WILLANS' ENGINE.

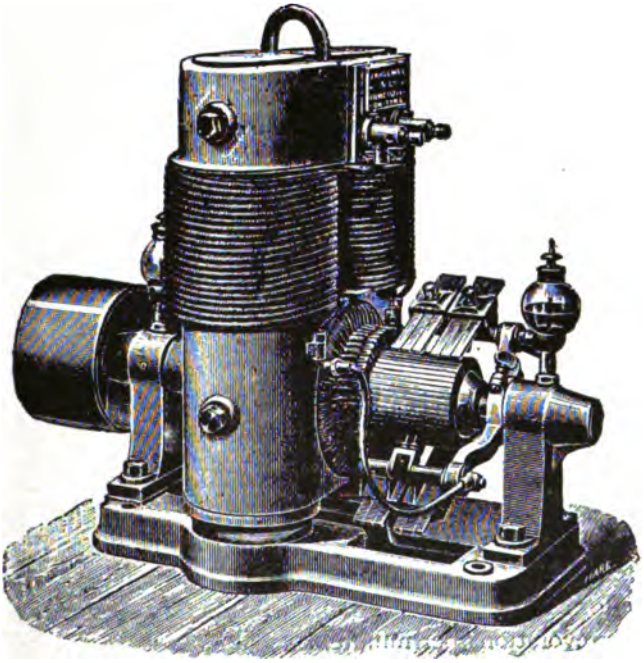
gular conductors built up of laminated or twisted copper strip, lightly oiled. The smaller are wound with round wire, silk covered. In Fig. 356 is illustrated a 61 kilowatt Goolden dynamo of the over-type, direct-driven at 460 revolutions per minute from a Willans' engine, so frequently used in central stations in England. The magnet limbs and pole-pieces are of wrought iron. The pole faces are bored elliptically, so as to leave greater air-space below armature than above, and counteract magnetic pull. The core-disks are of charcoal iron clamped upon a gun-metal spider. The conductor bars are driven by 80—100 fibre horns inserted in key-ways in the periphery of the core: they are united at ends by connectors made of spiral stamped plates of copper. At one end the bars are made fast to the segments of the commutator; at the other they are supported by an insulated brass ring, which allows them to expand longitudinally when they warm up. The commutator is of hard-drawn copper and mica, built up on a separate sleeve keyed to the shaft. The following tests were made of one of these combined plants, running at 500 revolutions per minute, showing the location of the various losses :—

	At Full Load.			At Half Load.		
Net output	..	50,000		..	25,000	
Loss in armature resistance ..	1,010			250		
Loss in magnet coils	615			590		
Loss by friction, eddy-currents, and hysteresis	255			255		
Total loss in dynamo	1,880	1,880		1,095	1,095	
Gross output	..	51,880	51,880	..	26,095	26,095
Loss in engine	..	..	5,920	..	..	5,920
Total indicated H.P. in watts ..	..	..	57,800	..	..	32,015
Commercial efficiency of dynamo.	96·2 per cent.			95·7 per cent.		
Commercial efficiency of combination	86·5 per cent.			71·8 per cent.		

HOLMES' DYNAMOS.

Messrs. J. H. Holmes & Co., of Newcastle-on-Tyne, have introduced a compact and well-built form of Gramme machine, depicted in Fig. 357. It is known as the "Castle" dynamo; its yoke and pole-piece are of cast iron, bored to receive the cylindrical upright wrought-iron cores. The ring armature core is made up of thin plates of charcoal iron. The commutator bars are forced together by hydraulic pressure before being clamped up. Messrs. Holmes have applied themselves very successfully to the problem of obtaining a constant output from a dynamo when driven at variable speeds.[1] The case in which this arises is in the lighting of

FIG. 357.



HOLMES' DYNAMO.

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[1] For various solutions of this problem see following Specifications of Patents: 342 of 1889 (mordey): 3420 of 1889 (Sayers): and 20,244 of 1889 (Holmes). Also P. Hoho; in *Bull. de la Soc. Belge d'Electriciens*, March, 1890.

railway trains by dynamos driven from the axles of one of the carriages. This they accomplished by a special combination of two dynamos, together with certain automatic switches. The larger dynamo is wound with two circuits upon the field-magnets, and its shaft is coupled to a smaller dynamo, the function of which is to send a demagnetizing current around the second circuit of the larger dynamo, so that as the speed rises its magnetism falls nearly in proportion. By this means the voltage is kept nearly constant, though the speed of the train may vary from 30 to 70 miles per hour.

LAURENCE, PARIS, AND SCOTT'S DYNAMOS.

In the modern machines by this firm the magnets are of the type Fig. 120, No. 8, with consequent poles, but more compact, and with deep nicks between the right and left-hand halves to diminish cross-magnetization. The armature conductors are bedded in deep narrow slots between iron teeth in the core disks, which are threaded upon a hexagonal steel shaft. When compound-wound the series coil are usually wound first, and on the upper core-limbs only. For large machines the series coils are of sheet copper, insulated with strips of calico. The following data relate to a "C 6" dynamo wound for 120 amperes at 100 volts, at 710 revolutions per minute. The same machine with shunt winding only would serve for charging accumulators with 60 amperes at 130 volts, at 910 revolutions per minute.

There are 52 sections in the commutator, and two complete turns of conductor between each section. The sectional area of the iron in the armature core is 29·7. Sectional area of magnet cast iron 98 square inch. The magnetic density when given 100 volts at 710 revolutions is nearly 138,000 lines per square inch. The armature conductor is of braided wire, and is extremely well insulated between inside and outside windings, and from the iron core.

Ampere turns in shunt 6468.

Ampere turns in series coils 3360.

The series winding consists of 28 turns of sheet copper 4½ inches wide, ·025 thick, on each of top magnets.

The current density in armature conductor is 3210 amperes per square inch, with 120 amperes

Resistance of shunt coils 32·4 ohms watts lost with 100 volts. .	308
,, series coils 0·0124 ,, ,, ,, 120 amps. .	178
,, armature coils 0·045 ohms watts lost with 120 amps. .	648
Total watts lost	1,134
Watts in external circuit	12,000
Total watts	13,134

showing an electrical efficiency of 91·4 per cent.

"TYNE" DYNAMOS.

These machines, constructed by Messrs. Ernest Scott & Co., from the designs of Mr. Mountain, have mostly four consequent poles and a cross-connected armature. The arrangements of commutator, brush-holders, and rocker are of great excellence, and are depicted on Plate XV. The mode of holding together the commutator is designed to prevent creeping of oil into its interstices.

LAHMEYER'S DYNAMO.

This machine,[1] the magnets of which belong to the iron-clad type, is depicted in Fig. 358. It has been submitted to elaborate tests by Professor W. Kohlrausch. The machine, weighing 597 kilogrammes, gave 60 amperes at 65 volts, with a speed of 1250 revolutions per minute. The current density in the armature was 8·3 amperes per square millimetre of copper in section. The commercial efficiency was over 80 per cent. Though the field-magnets of cast iron were magnetized up to only 36 per cent. of their maximum, the armature current showed very little demagnetizing tendency. According to the inventor the waste magnetic field is less than 8 per cent. of the total field generated. The armature is wound on a plan suggested by Arnold of Riga, and independently suggested by Crompton, namely, the conductors are wound between teeth in the periphery of the core, after which the whole exterior of the armature is served with a thin layer of insulating material, and over this a layer of iron wires is wound. More recently Herr Lahmeyer has constructed in Frankfort[1] multipolar dynamos of kindred type.

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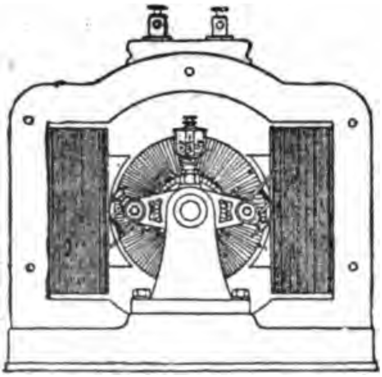
[1] See *Centralblatt für Elektrotechnik*, ix. 71 and 411, 1887; also *Elektrotechnische Zeitschrift*, ix. 89, 1888.

FIG. 858.



LAHMEYER'S DYNAMO.

"LEEDS" DYNAMO.

This machine (Fig. 359), made by Greenwood and Batley of Leeds, belongs to a type of machine with one exciting coil originated by the author (see Fig. 121, p. 200) in 1883. Similar designs have been used by Messrs. Goolden & Co., Messrs. Immisch, and Mr. R. Kennedy. The magnet-core is of soft wrought iron, the polar limbs—the lower one of which is in one piece with the bed-plate—are of annealed cast iron. The armature is ring-wound in a single layer, and is provided with a commutator of unusual length. The following are the dimensions of "Leeds" dynamos supplied to the Cadogan lighting station at Chelsea:—

35 kilowatt dynamo: Output, 70 amperes at 500 volts, 30 HP., at 800 revolutions per minute. Section of iron in armature core 84 sq. inches; in magnets 87 sq. inches. Total length

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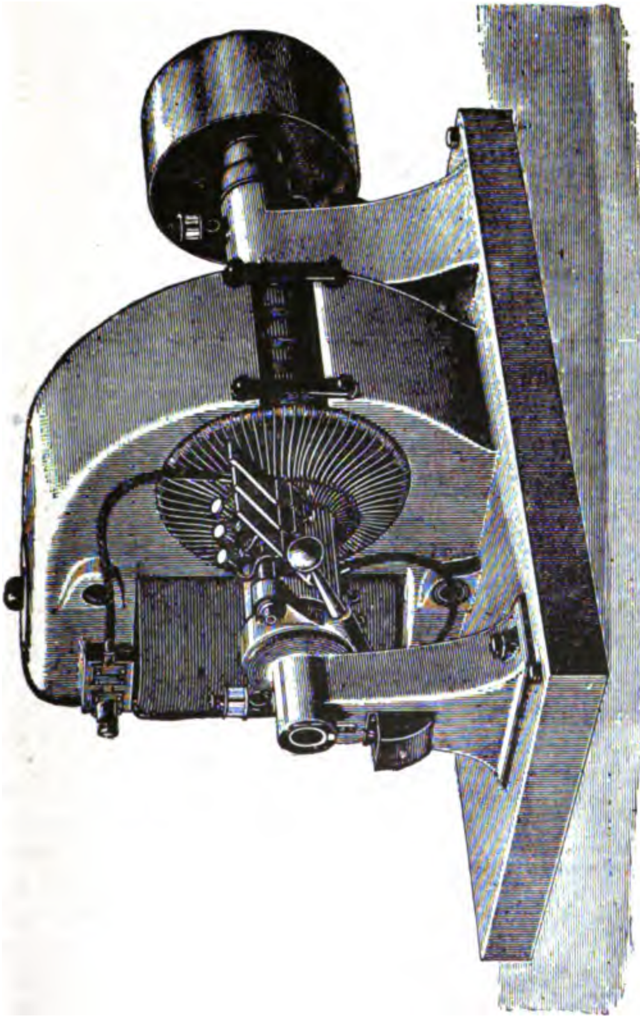
[1] See *Electrical Review*, xxix. 404, 1891.

of magnetic circuit 85 inches; ampere-turns on magnet 39,000. Air-gap, 345 sq. inches, by 0·57 inch from core to pole surface. $B_{\prime\prime} = 86{,}400$. Diameter of armature (outside) 18·5 inches; length ditto, 14 inches; peripheral speed, 3900 feet per minute; weight of copper in armature, 115 lbs.; current density in armature, 3750 amperes per sq. inch; total turns in armature winding, 560; number of bars of commutator, 80.

FIG. 359.



THE "LEEDS" DYNAMO.

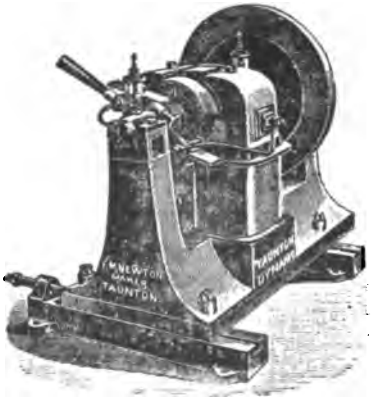
ELWELL-PARKER DYNAMOS.

Plate VI. depicts a 2-pole drum machine of 20 kilowatt capacity made by the Electric Construction Corporation, who have given the following particulars:—*Output:* 200 amperes at 100 volts; requiring 28½ HP. at 900 revolutions per minute. *Armature:* Core-disks 11¼ inches external diameter, 2¼ inches internal diameter. Number of conductors 104, each 0·05 square inch in section. Resistance 0·0154 ohm. Commutator has 52 segments, 6⅛ inches in length. *Field-magnet:* compound wound; resistance of shunt 28 ohms; of series winding 0·0021 ohm. The field-magnets of these machines are made up of several bars of wrought iron, with a thin cast-iron cap over the pole-pieces. The core-disks are threaded direct on the shaft. The chief insulating material used is a preparation of paper, impregnated with a special varnish. This firm has also constructed large 4-pole drum machines for central-station lighting.

"TAUNTON" DYNAMOS.

Messrs. Newton of Taunton produce excellent little machines, Fig. 360, of the same type as the preceding. One of these examined by the author ran absolutely sparklessly at all loads.

FIG. 360.



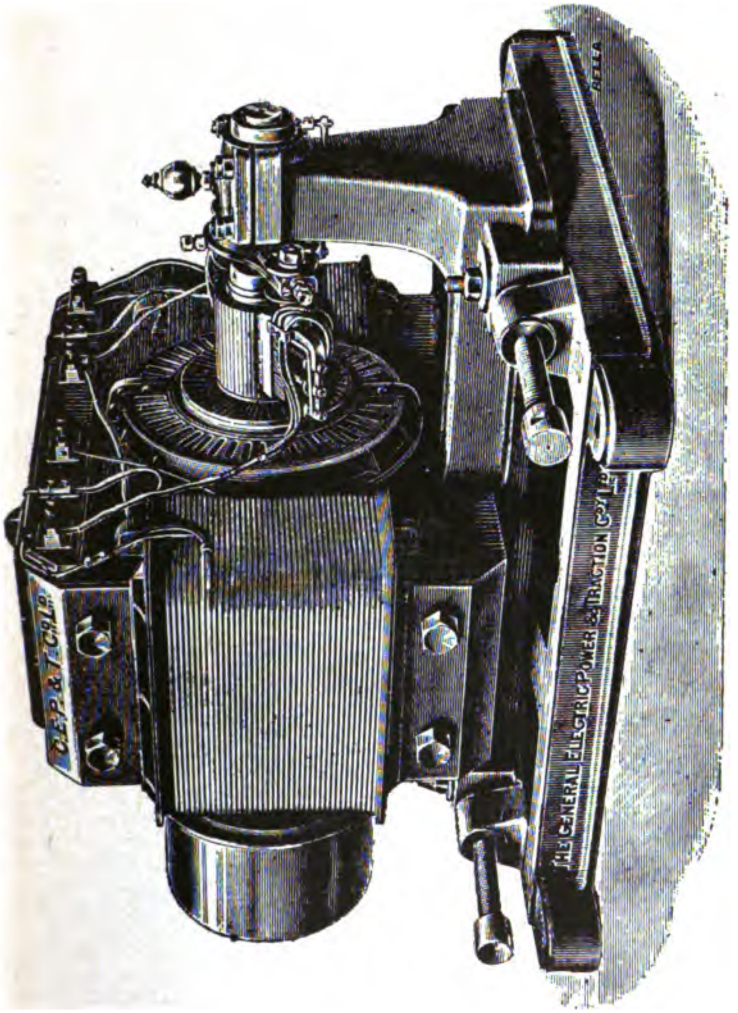
THE TAUNTON DYNAMO.

GENERAL ELECTRIC TRACTION COMPANY'S DYNAMOS.

This firm has devoted itself to machines suitable for traction and mining purposes. The machine depicted in Fig. 361 was built from the designs of Mr. A. T. Snell. It has wrought-iron cores and cast-iron polar yoke pieces in the magnets. The brushes are of carbon; the holder is the same depicted in Fig. 277

(p. 382). This firm has also produced some large 4-pole dynamos of the same type as Fig. 1, Plate IX.

Fig. 361.

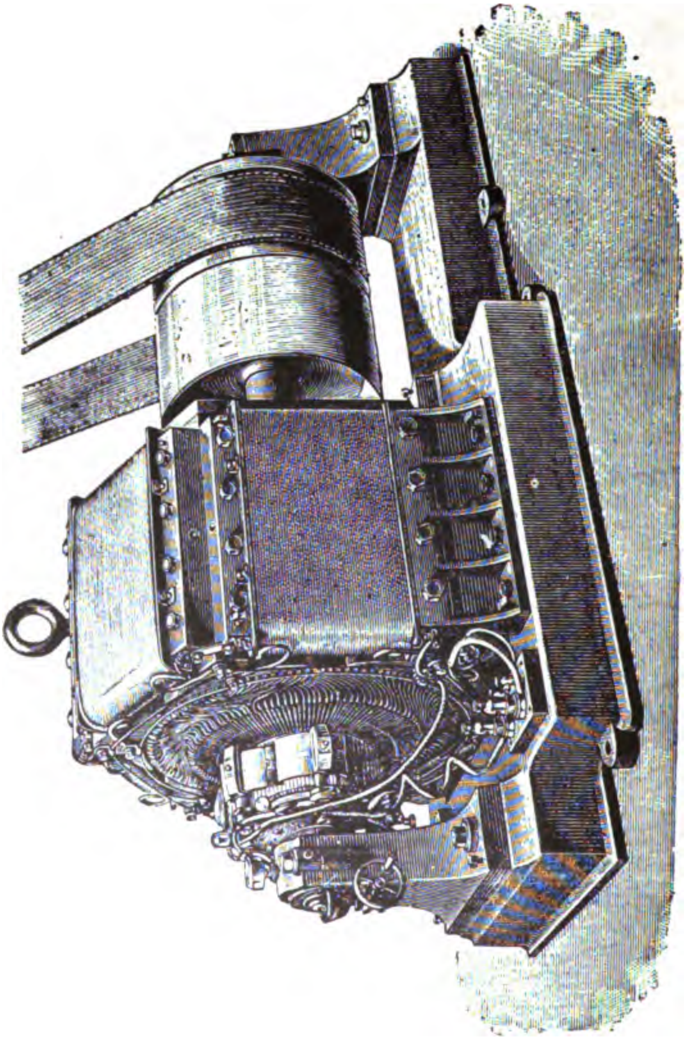

THE GENERAL ELECTRIC POWER & TRACTION Co. Ld.
G.E.P.&T.Co.Ld.
BELLA

General Electric Traction Company's Dynamo.

Other Multipolar Dynamos.

In recent years various other multipolar forms have appeared for central-station work. The Allgemeine Company of Berlin has constructed large 12-pole machines,[1] as well as 6-pole and 4-pole drum dynamos. The Thomson-Houston Company has designed a large 4-pole drum[2] closely

FIG. 362.



THURY'S DYNAMO.

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[1] *Elektrotechnische Zeitschrift*, x. Sept., 1889.
[2] *Electrical World*, xiv. 335, 1889.

resembling Fig. 1, Plate IX. Large machines have also been turned out by Messrs. Latimer Clark, Muirhead & Co. of Westminster.[1] Messrs. Alioth & Co.[2] of Basel also construct multipolar drum dynamos. The Westinghouse Company is designing some large 6-pole machines.

THURY'S DYNAMO.

A 6-pole hollow-drum dynamo by Thury of Geneva is shown in Fig. 362. The method of the winding is described on p. 330, and the detail of the field-magnet on p. 201.

WENSTROM'S DYNAMO.

This form, which made its appearance in Sweden in 1882, has field-magnets of the iron-clad type, with two salient pole-pieces upon which the coils are borne, an external cylinder of iron, which encloses the machine, serving as the yoke. The armature has the peculiarity that the coils are wound in circular holes notched into the periphery of the armature core.

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[1] *Electrical World*, xiii. 284, 1889.

[2] *La Lumière Electrique*, xxxii. 522, 1889.

CHAPTER XIX.

MISCELLANEOUS DYNAMOS.

In this chapter are included Dynamos for Electrometallurgy, Unipolar Dynamos, Disk-Dynamos and other miscellaneous forms.

DYNAMOS FOR ELECTROPLATING AND ELECTROMETALLURGY.

Special forms of dynamo are needed for the work of electroplating, electrotyping, and the electrolytic treatment of ores and purification of metals. They must, of course, be of the continuous-current type. In general, very low electromotive-forces and very large currents are requisite, for the quantity of metal deposited in the bath depends upon the quantity of amperes of current only, and not on the number of volts of electromotive-force. And though a few volts are necessary to drive the requisite current through the resistances of the circuit, the number is in every case small. To decompose water electrolytically requires less than two volts. To deposit metal in a bath in which the anode is of the same metal as the deposit requires usually a very small electromotive-force. In general, if too great an electromotive-force is employed, or if the density of current (*i. e.* the number of amperes per unit of area of kathode surface) is permitted, the metallic deposits will be uneven or pulverulent. All these circumstances point to the construction of dynamos having at most but four or five volts of electromotive-force, but so designed as to have an exceedingly low internal resistance.

The first application of a dynamo to the purpose of electroplating is due to Mr. J. S. Woolrich, who in 1842 patented this use of a magneto-electric machine. Wilde, however, was the first to construct machines really fitted for the purpose, when he invented the principle of using a large dynamo, the field-magnets of which were separately excited by the currents of a smaller magneto machine. His first machines, which were used for many years by Messrs. Elkington, had small exciters of the old Siemens type (Fig. 23), mounted upon electromagnets of the form shown in Fig. 119, No. 1. Both armatures were of the old shuttle-form introduced by Siemens, and the larger one required to be kept cool by streams of water. About the year 1867 Wilde introduced another type of machine, to which reference was made on p. 12. The armature coils (save the one used for feeding the field-magnets) are connected in parallel in the manner shown in Fig. 417. There are iron cores in the armature coils of this machine, which is, in consequence, prone to heat. Weston introduced a small machine for nickel-plating which had steel cores to the magnets but with main-circuit coils upon them, and an automatic cut-off to break the current, to prevent the magnetism from reversing by a back-current from the bath. Elmore introduced another machine with multipolar magnets and disk armature. The commutator merely rectified the currents (p. 40) without rendering them continuous. This is a bad feature: for with all electro-chemical work, whether plating, typing, or charging accumulators, there is necessarily much sparking, unless the fluctuations of the current are reduced to a minimum by employing a many-part armature with a proper collector. The largest Elmore dynamos, for copper refining, had eighteen electromagnets in each crown, and yielded a current of 3000 amperes at a potential of seven to eight volts. Such a machine would deposit over 25 lbs. of copper per hour. The field-magnet coils are in series with the main circuit. This is a mistake. All electroplating dynamos should be shunt-wound or they are liable to reverse. Gramme in 1873 built special forms of very low resistance with strip-wound armatures having a commutator at each end, and giving 1500 amperes at 8 volts. Siemens and Halske also were early in the field with machines having bar armatures, which they employed at their electrolytic works at Oker.[1] Brush also constructed machines of low resistance for electroplating purposes. It was for this type of machine that Brush made the important invention of exciting the field-magnets with a compound winding; coarse wire coils being connected in series, with the addition of a so-called "teazer" coil of finer wire—in other words, a shunt winding—to maintain the magnetism when the main circuit was opened, thus enabling the machine to do either a large or a small amount of work without fear of reversing the current. The potential at the terminals of this machine is fairly constant. It varied only from 3·3 to 4·1 volts, whilst the current varied from 300 amperes to zero.

Other dynamos have been designed for electroplating and electro-metallurgical work by nearly all the important manufacturers.

An Elwell-Parker depositing dynamo[2] gave 1500 amperes at 50 volts at 450 revolutions per minute; a 4-pole shunt-wound drum machine with 80 stranded conductors, each of 0·2 square inch section, on the drum, and a 40-part commutator. Armature is 20 inches long and 22 inches diameter, with an unusually long commutator. Four sets of brushes, five in each set. Length of active conductor 1600 inches. At peripheral speed of 2500 feet per minute generates 1 volt for each 8 inches of conductor.

A 50 kilowatt dynamo, by Paterson and Cooper,[3] for producing bleaching liquor electrolytically, gives 1200 amperes at 42 volts.

Another 50 kilowatt dynamo, designed by Hopkinson[4] for copper refining, gives 1000 amperes at 50 volts, at 400 revolutions per minute; resistance of armature 0·0016 ohm; commercial efficiency 93 per cent.; total weight 5¼ tons.

A plating dynamo by Stafford and Eaves[5] has solid and simple magnetic circuit with one exciting coil and a ring armature with only eighteen sections, giving 150 amperes at 6 volts at 640 revolutions per minute.

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[1] See *Elektrotechnische Zeitschrift*, ii. 54.

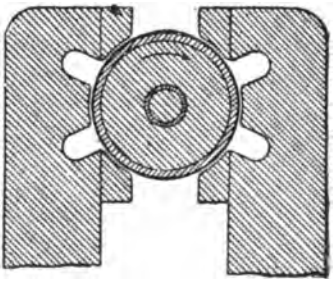
[2] *The Electrician*, xxi. 183, 1888.

[3] *Ibid.*, p. 181. [4] *Ibid.*, xvii. 62, 1886. [5] *Ibid.*, xviii. 506, 1887.

In dynamos for such purposes the requirement of large current and very low voltage introduces difficulties into the design, for the voltage cannot be obtained low enough without having either very few convolutions on the armature, or else a weak field-magnet, or else a very slow-speed machine. Slow-speed machines are always costly in proportion to their output. Machines with weak magnets give trouble with sparking. Machines with few massive conductors and few parts in commutator give trouble in sparking, and are liable to heat from local eddy-currents. A stranded conductor should be used, or several *independent* windings (see pp. 315 and 509), all put in parallel by brushes of special thickness.

Sayers has proposed an ingenious device to enable currents to be taken from a machine at various voltages. The pole surfaces are subdivided by deep nicks, as in Fig. 363, thus providing several neutral points on the commutator at which brushes may be placed without sparking. Thus, for example, whilst the potential between the two main brushes may be 10 volts, an intermediate brush may be employed to divide this into 7½ volts for nickeling and 2½ volts for silver-plating.

Fig. 363.



Sayers' Dynamo for Electroplating.

Messrs. Crompton & Co. have devised a method of dividing the main leads between two pairs of brushes touching adjacent bars of the commutator, and are thereby enabled to construct their plating machines with fewer parts in the armature. The divided leads from the dynamo to the plating tanks cost no more than a single undivided lead would do, but they interpose a comparatively large resistance in the path of the local current from the short-circuited section.

For the special purpose of the aluminium industry several types of machines have been developed. Messrs. Crompton

& Co. built a very large 2-pole drum machine,[1] capable of affording 5000 amperes at 60 volts. Mr. C. E. L. Brown[2] has made some 6-pole machines for 6000 amperes at 20 volts at 180 revolutions per minute. The armatures have each two separate windings with a commutator at each end, and at each commutator 36 brushes, arranged in six sets of six each. The field-magnet is like Fig. 131, but with six poles, and cast in one piece. The armature is 38 inches in diameter and 24 inches long. The windings were at first embedded in holes in the core-disks; but as troubles arose about insulation, the core-disks were turned down, and the armature re-wound with external conductors. Although there are as many brush-sets as poles, rendering cross-connexion of the windings not absolutely necessary, yet such cross-connexions are added to ensure equalization of the currents, equipotential segments of the commutator being internally cross-connected by rings with three projecting lugs. Mr. Brown has also made some 8-pole machines for an output of 14,000 amperes at 30 volts.

NUMERICAL STATISTICS ON ELECTRO-METALLURGY.

The following data are useful for reference in deciding what the electrical capacity of a dynamo must be in order that it may deposit metal in any desired quantity:—

Copper.

Current	1	ampere	deposits	0·000326	grammes	per second.
"	1	"	"	0·01957	"	per minute.
"	1	"	"	1·1739	"	per hour.
"	851·8	"	"	1	kilogramme	per hour.
"	386·4	"	"	1	pound	per hour.

To deposit 100 lbs. of copper in a working day of 10 hours will require 3864 amperes of current flowing all the time; or, if conducted in ten baths in series with one another, will require 386·4 amperes, but in that case the dynamo will require to be of an electromotive-force ten times as great as for one single large bath. If electrolysis of the crude copper solution is carried on with carbon anodes, there will be required about 1·2 volts for each bath in series, or, at most, 15 volts for the ten baths.

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[1] *The Electrician*, xxi. 590, 1888; also *La Lumière Electrique*, xxx. 207, 1888.

[2] *La Lumière Electrique*, xxx. 205, 1888.

Silver.

Current of	1	ampere	deposits	4·025	grammes	per	hour.
„ „	112·7	„	„	1	pound	per	hour.

Gold.

Current of	1	ampere	deposits	2·441	grammes	per	hour.
„ „	185·8	„	„	1	pound	per	hour.

Nickel.

Current of	1	ampere	deposits	1·099	grammes	per	hour.
„ „	412·8	„	„	1	pound	per	hour.

The following statistics as to the various pressures and currents required in various processes of electro-deposition are useful for reference:—

PRESSURE AT TERMINALS REQUIRED FOR DIFFERENT KINDS OF BATHS.

	Volts.
Copper (acid bath)	0·5 to 1·5
„ (cyanide bath)	3 „ 5
Silver	0·5 „ 1
Gold	0·5 „ 4
Brass	3 „ 5
Iron (steel facing)	1 „ 1·3
Nickel on iron, steel, copper, with nickel anode, strike deposit with 5 volts, diminishing to	1·5 „ 2
Nickel on iron, steel, copper, with carbon anode	2 „ 4
Nickel on zinc	4 „ 7
Platinum	5 „ 6

CURRENT DENSITY FOR PROPER DEPOSIT.

Copper Typing—	Amperes per 100 sq. inch.
Best quality tough deposit	1·5 to 4
Good and tough (for clichés)	4 „ 10
Good solid deposit	10 „ 25
Solid deposit, sandy at edges	25 „ 40
Sandy and granular deposit	50 „ 100

	Amperes per 100 sq. inch.		
Copper (cyanide bath)	2	to	3
Zinc (for refining)	2	,,	3
Silver	1	,,	3
Gold	0·5	,,	1
Brass	3	,,	3·5
Iron (steel facing)	0·5	,,	1·5
Nickel at first deposit 9 to 10 amperes per 100 square inches, diminishing afterwards to	1	,,	2

UNIPOLAR DYNAMOS.

Those dynamos in which rotation of a conductor effects a continuous increase in the number of lines of force cut, by the device of arranging one part of the conductor to slide on or round the magnet, are known [1] as *unipolar* machines.

The earliest machine which has any right to be called a dynamo (Fig. 1, p. 6), namely, the rotating copper disk of Faraday, was, in fact, of this class. So were his other machines with sliding connexions; for example, the copper cylinder rotating over the pole of a magnet (Fig. 3, p. 7). Plücker [2] devised another form, with a horizontally rotating magnet, having sliding contacts at the middle and at either end. In 1862 Mr. S. A. Varley had a unipolar apparatus with an iron magnet rotating in a vertical frame having a mercurial connexion at the middle-point. About 1878 Dr. Werner Siemens [3] designed a unipolar machine in which there were two cylinders of copper, both slit longitudinally to obviate eddy-currents, each of which rotated round one pole of a U-shaped electromagnet. A second electromagnet was placed between the rotating cylinders, with protruding pole-pieces of arching form which embraced the cylinders above and below.

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[1] This sounds like a *lucus a non lucendo*, for the magnet has two poles. But the name is derived from the term "unipolar induction," which continental electricians, following Prof. Wm. Weber, give to the induction of currents by the process of "continuous cutting," which we are now dealing with. I do not adopt the term, as it is needlessly mystifying.

[2] *Pogg. Ann.*, lxxxvii. 352, 1852.

[3] *Elektrotechnische Zeitschrift*, ii. 94, 1881.

Each cylinder, therefore, rotated between an internal and an external pole of opposite polarity, and consequently cut the lines of force continuously by sliding upon the internal pole. The currents from this machine were very great, but of only a few volts of electromotive-force. To keep down the resistance, many collecting brushes pressed on the cylinders at each end. This dynamo was used at Oker for depositing copper. Much attention has been paid in recent years to machines of this type, and the author himself designed one in which two Faraday disks, coupled at their peripheries outside an internal stationary pole-piece, rotate in a symmetrically uniform field. Mr. Willoughby Smith showed that if an iron disk be used instead of a copper disk a much more powerful effect is obtained. Prof. George Forbes has constructed several machines of this class. Originally he began by employing an iron disk which rotated between two cheeks of opposite polarity, the current being drawn from its periphery. He then doubled the parts. The next stage was to unite the two disks into one common cylinder, rotating within an entirely self-contained iron-clad field-magnet. For this reason the inventor prefers to call this type of dynamo "non-polar." A rubbing contact—for which purpose Prof. Forbes at one time used carbon brushes, and at another a number of springy strips of metal foil—is maintained at the two extremities of the periphery. One of the earlier forms of machine, with a single disk 18 inches in diameter, was stated to give 3117 amperes at a potential of 5·8 volts when running at 1500 revolutions per minute. One of the later machines, in which the armature is a cylinder of iron 9 inches in diameter, 8 inches long, is designed to give a current of 10,000 amperes at 1 volt, at 1000 revolutions per minute. The electromotive-force of such machines increases as the square of the diameter. Other types have been designed by E. Ferraris, E. L. Voice, Delafield, Hummel, and others. All the important forms prior to 1885 are described and discussed by Uppenborn in the *Centralblatt für Elektrotechnik* of that year, p. 324.

Two difficulties seem to beset this type of machine, namely, the inherent trouble of peripheral collection of large currents, and the very considerable armature reactions which accompany these large currents, causing great fall in the voltage[1] as the current increases. The latter can only be obviated by the same expedients as hold good in all other types of dynamo, namely, to make the field-magnets relatively powerful and to counterbalance the reactions by compounding or over-compounding the machine by the use of series windings.

The theory of the unipolar disk-dynamo has been given by Sir W. Thomson,[2] who has shown that such a machine is not self-exciting except above a certain critical speed, dependent on the resistance of the circuit. The latest suggestions came from Atkinson,[3] whose machine is self-exciting, and Mr. C. E. L. Brown has communicated to the author some results and drawings of a unipolar machine built at the Oerlikon Works, with a cylinder of copper rotating between the lips of an iron-clad electromagnet of cast-iron. This machine at 1200 revolutions per minute worked at 10 volts and showed hardly any perceptible drop in voltage when 3000 amperes were taken from it.

DISK-DYNAMOS.

In the dynamos of this class the coils are carried round to different parts of a magnetic field, such that either the intensity differs in different regions, or more generally the lines of force run in opposite directions in different parts of the field. Fig. 17 (p. 29) illustrates this principle; and we shall now consider how it is carried out in practice. In the early machines of Saxton, Clarke, and Stöhrer, single pairs of coils were mounted so as to pass in this fashion through parts of the field where the magnetic induction was oppositely directed. Such a machine will, therefore, give alternate currents, unless a commutator be affixed to the rotating axis. Niaudet's obsolete dynamo, which may be regarded as a compound Saxton machine, having the separate armature coils united as those of Gramme and Siemens into one continuous circuit, was furnished with a radial collector instead of a cylindrical one. In the Wallace-Farmer dynamo was very nearly realized the condition of field of Fig. 17, there being a pair of poles at the top arranged so that the N. faces the S. pole, and another pair at the bottom where the S. faces the N. pole. In 1878 von Hefner Alteneck designed a disk-dynamo in which the number of coils differed by two, or some other number, from those of the field, and with the employment of a multiple bar commutator with complicated cross-connexions. In 1881 Hopkinson and Muirhead showed a disk-dynamo with a wave-winding. In 1875 Professor Pacinotti devised[1] a form of disk-armature, which he described as a "transversal electromagnetic fly-wheel." The machine, which was exhibited at Paris in 1881, had for field-magnet two electromagnets placed with their contrary poles juxtaposed, forming, as shown in Fig. 364, a single magnetic circuit with two gaps. Through these two gaps passed a disk-armature, constructed of radial conductors arranged to cut the intense magnetic fields. The electromotive-forces induced in these conductors would on the one side be directed radially inwards, on the other radially outwards. The method devised by Pacinotti for connecting the radial conductors into a single closed coil is shown in Fig. 233, p. 338. Another form was the obliquely-coiled dynamo of Ayrton and Perry of 1882. Another disk-armature was designed about the same time by Mr. Edison with radial bars, connected at the outer ends by concentric hoops and at the inner by copper washers. A more recent form of the same inventor is shown in Fig. 235, p. 340. Another type of disk-armature was invented by Sir W. Thomson, consisting of a

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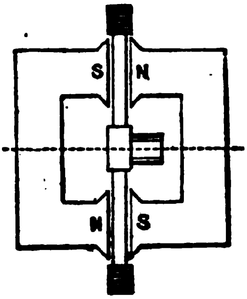
[1] See some figures given by Hummel in vol. ii. p. 19, of Kittler's *Handbuch der Elektrotechnik.*

[2] On a uniform electric current accumulator (*Phil. Mag.*, January 1868; and *Reprint of Papers*, p. 325).

[3] *La Lumière Electrique*, xxxv. 557, 1890.

FIG. 364.



FIELD-MAGNETS OF PACINOTTI'S DISK-DYNAMO.

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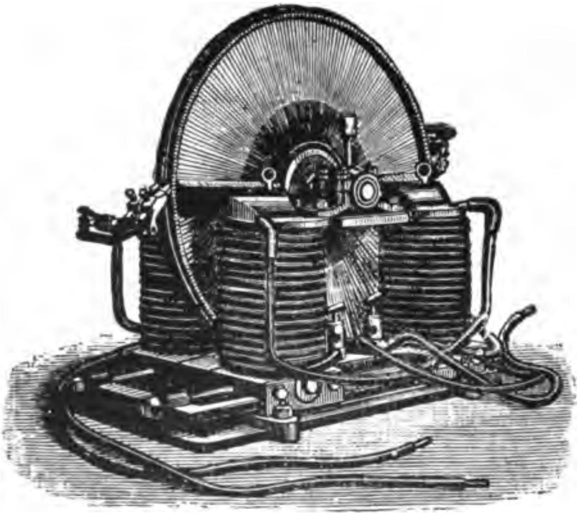
[1] *Nuovo Cimento* [3] x., September 1881.

wheel with spokes like a bicycle wheel, with collecting brushes pressing against opposite ends of a diameter. Bollman[1] devised a multipolar machine, having a complex armature built up of radial strips of copper connected in zigzag and joined to a cross-connected commutator. More recently machines of this class have been devised by Desroziers,[2] Robin,[3] Jehl and Rupp,[4] and Sayers.[5] In the machine of Jehl and Rupp, which is brought out by the French Edison Co., there are four pairs of opposing poles.

FIG. 365.



POLECHKO'S DISK-DYNAMO.

With 24 kilogrammes of copper in the armature, and running at 735 revolutions per minute, this machine gives 350 amperes at 110 volts.

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[1] For detailed drawings and description, see *Centralblatt für Elektrotechnik*, ix. 7, 1887.

[2] See *La Lumiere Electrique*, xxiv. 293, 294, and 517, 1887; xxix. 401 1888.

[3] *Ibid.*, xxiv. 544, 1887.

[4] *Ibid.*, xxiv. 343, 1887. See also detailed illustrations and description in xxv. 368, 1887; and in *Electrician*, xix. 94, 1887.

[5] Specification of Patent, 717 of 1887.

Fritsche's Disk-Dynamos.—These dynamos[1] have a disk with multipolar wave-winding with series grouping for armature. The interesting constructional feature of these machines is the use of wrought-iron bars, instead of copper, as the active conductors in the disk. The commutator is fixed to the outside of the disk, with the brushes trailing against the periphery at two points.

Polechko's Dynamo.—This form[2] realizes Sir W. Thomson's suggestion for a wheel-dynamo. The wheel is 1 metre in diameter, with narrow copper spokes to rotate in a narrow gap between the pole-pieces of a pair of electromagnets, arranged to produce a very intense narrow magnetic field along two opposite radii. Fig. 365 shows its form, and the arrangement for collecting the current from the periphery, which is made up of 320 insulated pieces of copper strongly held together by an insulated steel ring at the middle of the rim. It gave, at 1500 revolutions per minute, a current of 2000 amperes at 25 volts; the entire machine weighing 1·1 tons.

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[1] See Fritsche's book, *Die Gleichstrom-Dynamomaschine*, Berlin, 1889; also Specification of British Patent, No. 13,080 of 1887. See also *The Electrician*, xxii. 655, 1888; also *Electrical Review*, xxix. 472, 1891; and *Electrical World*, xii. 205, 1889.

[2] *Journal de la Société Physico-chimique russe*, xxii. 135, 1890.

CHAPTER XX.

ELECTRIC MOTORS (CONTINUOUS CURRENT).

In the first chapter, the definition was laid down that dynamo-electric machinery meant "machinery for converting energy in the form of mechanical power into energy in the form of electric currents, or *vice versâ*." Having dealt with the dynamo in its function as a generator of electric currents, we now come to its converse function, namely, that of converting the energy of electric currents into the energy of mechanical motion.

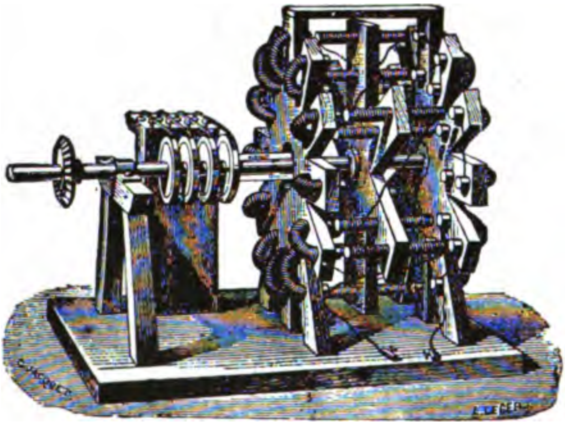
An *electric motor*, or, as it was formerly called, an *electromagnetic engine*, is one which does mechanical work at the expense of electric energy; and this is true, no matter whether the magnets which form the fixed part of the machine be permanent magnets of steel or electromagnets. In fact, any kind of dynamo, whether for continuous currents or alternating currents, can be used conversely as a motor, though, as we shall see, some more appropriately than others.

Every one knows that a magnet will attract the opposite pole of another magnet, and will pull it round. We know also that every magnet placed in a magnetic field tends to turn round and set itself along the lines of force.

It is not, therefore, difficult to understand that very soon after the invention of the electromagnet, which gave us for the first time a magnet whose power was under control, a number of ingenious persons perceived that it would be possible to construct an electromagnetic engine, in which an electromagnet, placed in a magnetic field, should be pulled round; and, further, that the rotation should be kept up continuously, by cutting off or reversing the current at an appropriate moment. As a matter of fact, a mere coil of wire carrying a current, is acted upon when placed in the magnetic field, and is pulled round as a magnet is. On this very principle was constructed the earliest electric motor of Ritchie, so well known in many forms as a stock piece of electric apparatus, but little better in reality than a toy. Joule[1] also devised several forms of electric motor.

A great step in advance was made by Jacobi, who, in 1838, constructed the multipolar machine of which we give a representation in Fig. 366. This motor, which Jacobi designed for his electric boat, had two strong wooden frames, in each of which a dozen electromagnets were fixed, their poles being set alternately. Between them, upon a wooden disk, was placed another set of electromagnets, which, by the alternate attraction and repulsion of the fixed poles, were kept in rotation; the current which traversed the rotating magnets being regularly reversed at the moment of passing the poles of the fixed magnets by means of a commutator, consisting, according to Jacobi's directions, of four brass-toothed wheels having pieces of ivory or wood let in between the teeth for insulation. Jacobi's motor was, in fact, a very advanced type

FIG. 366.



JACOBI'S ELECTRIC MOTOR.

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[1] *Annals of Electricity*, ii. 222, 1838; and iv. 203, 1839.

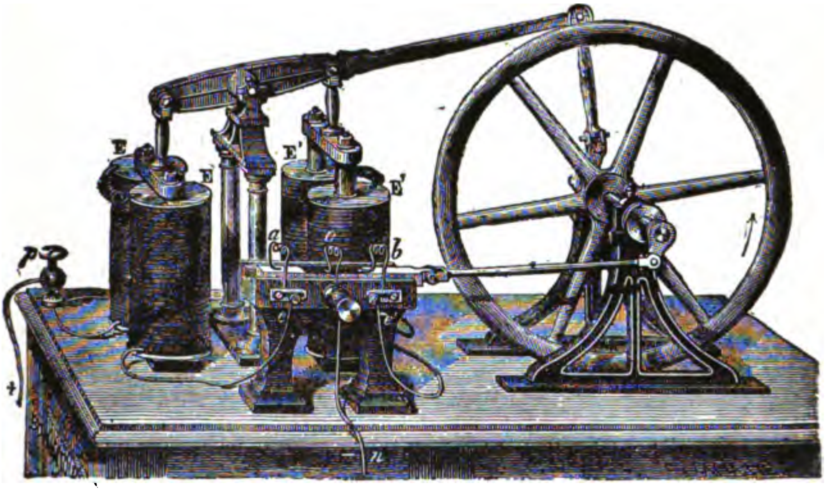
of dynamo, and would, of course, generate currents if driven round by mechanical power.

A still earlier rotating apparatus, and, like Ritchie's motor, a mere toy, was Sturgeon's wheel-disk, described in 1823. This instrument, interesting as being the forerunner of Faraday's disk dynamo, is the representative of a distinctive class of machines, namely, those which have a sliding contact merely, and need no commutator.

Another class of motors may be named, wherein the moving part, instead of rotating upon an axis, is caused to oscillate backwards and forwards. Professor Henry, to whom we owe so much in the early history of electromagnetism, constructed, in 1831, a motor with an oscillating beam, alternately drawn backwards and forwards by the intermittent action of an electromagnet. Dal Negro's motor of 1833 was of this class; in it a steel rod was caused to oscillate between the poles of an electromagnet, and caused a crank to which it was geared to rotate in consequence. A distinct improvement in this type of machine was introduced by Page, who employed hollow coils or bobbins as electromagnets, which, by their alternate action, sucked down iron cores into the coils, and caused them to oscillate to and fro, Motors of this kind form an admirable illustration of one of the laws of electromagnetics, first formulated by Gauss, but developed later by Maxwell, to the effect that a circuit acts on a magnetic pole in such a way as to make the number of magnetic lines of force that pass through the circuit a maximum.

Page's suggestion was further developed by Bourbouze, who constructed the curious motor depicted in Fig. 367, which looks uncommonly like an old type of steam engine. We have here a beam, crank, fly-wheel, connecting-rod, and even an eccentric valve-gear and a slide-valve. But for cylinders we have four hollow electromagnets; for pistons, we have iron cores that are alternately sucked in and drawn out; and, for slide-valve we have a commutator, which, by dragging a pair of platinum-tipped springs over a flat surface made of three pieces of brass separated by two insulating strips of ivory, reverses at every stroke the direction of the currents in the coils of the electromagnets. It is really a very ingenious machine, but, in point of efficiency, far behind all modern electric motors. Unfortunately, it does not do to design dynamo-electric machinery on the same lines as steam engines.

Fig. 367.



Bourbouze's Electric Motor.

Yet another now obsolete class of electric motors owed its existence to Froment, who, fixing a series of parallel iron bars upon the periphery of a drum, caused them to be attracted, one after the other, by an electromagnet or electromagnets, and thus procured a continuous rotation.

Lastly, of the various historical types of motor we may enumerate a class in which the rotating portion is enclosed in an eccentric frame of iron, so that as it rotates it gradually approaches nearer. Little motors, working on this principle of "oblique approach," were invented by Wheatstone, and have long been used for spinning Geissler tubes, and other light experimental work. More recently, Trouvé and others have sought to embody this principle in motors of more ambitious proportions, but without securing any advantage; for it would be better to bring the armature close to the pole-pieces of the field-magnet.

It is impossible, within the limits of this work, to deal with a tithe of all the various stages of discovery and invention, or with many interesting and curious machines that have from time to time been tried. It might be told how Page, after inventing his machine in 1834, succeeded in 1852 in constructing a motor of such a size that he was able to drive a circular saw and a lathe by it. Space fails to describe the electric motor of Davidson, which, in 1842, enabled him to propel a carriage, at the speed of four miles an hour, between Edinburgh and Glasgow. An engine which was of 10 horse-power was built in 1849, by Sören Hjorth, at Liverpool.[1] Other inventions are alluded to in the Historical Notes at the beginning of this book. Two notable steps were the invention, in 1855, of the shuttle armature of Siemens, and in 1864 of the ring armature by Pacinotti. But the real development came after the commercial introduction of Gramme's dynamos in 1871, as engineers began to understand how two of these machines could be used—one as generator, the other as motor—to transmit power through a line. The modern dynamo, with its distinct organs the field-magnet and the armature, has superseded all the older types of motor.

All the earlier attempts to introduce electric motors came to nothing, for two reasons. Firstly, at that time there was no economical method of generating electric currents known; secondly, the great physical law of the conservation of energy was not fully recognized, and its all-important bearings upon the theory of electric machinery could not be foreseen.

While voltaic batteries were the only available sources of electric currents, economical working of electric motors was hopeless; for a voltaic battery wherein electric currents are generated by dissolving zinc in sulphuric acid is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work,[1] an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

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[1] An excellent account of the early forms of electric motor, both European and American, is to be found in Martin & Wetzler's *The Electric Motor and its Applications*, third edition, 1891. All readers interested in the subject should also consult the paper on *Electro-magnetism as a Motive Power*, by the late R. Hunt in *Proc. Inst. Civil Engineers*, xvi., April 1857, together with the discussion that followed it, in which part was taken by Professor Thomson (now Lord Kelvin), Mr. (now Sir William) Grove, Professor Tyndall, Mr. Cowper, Mr. Smee, and Mr. Robert Stephenson. They should also consult Kapp's *The Electric Transmission of Power.*

The fact, however, which seemed most discouraging, and which, if rightly interpreted in accordance with the law of conservation of energy, would have been found to be (on the contrary) a most encouraging fact, was the following:—If a galvanometer was placed in the circuit with the electric motor and the battery, it was found that when the motor was running the battery was unable to force through the wires so strong a current as that which flowed when the motor was standing still. The faster the motor ran, the weaker did the current become. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or else a counter electromotive-force. At first, the common idea was, that when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi[2] enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter electromotive-force (or "electromotive-force of reaction") which was developed. In fact, the theory of the conservation of energy requires that such a reaction should exist. Joule,[1] by further experiment, found that the counter electric action is proportional to the velocity of rotation and to the magnetism of the magnets.

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[1] A convenient way of regarding the economic question from the point of view of the cost of the voltaic battery is afforded by the following calculation. Supposing the electric motor to convert all the electric energy of the battery without loss into mechanical energy, the amount of zinc used per horse-power in one hour will be almost exactly two pounds divided by the volts of electromotive-force of the cell employed in the battery.

[2] *Memoire sur l'application de l'électromagnétisme au mouvement des machines* par M. H. Jacobi (Potsdam, 1835). On p. 45 of this memoir Jacobi points out that the motor, when set into rotation by the current of the battery, becomes by virtue of its motion a magneto-electric apparatus capable of generating a current in a counter-direction in the circuit; and to this he rightly attributes the limit of uniform speed obtained by the motor.

Two points are vital to the right understanding of the action of electric motors: (1) The propelling drag, (2) the counter electromotive-force. The first is that the real driving-force which propels the revolving armature is the drag which the magnetic field exerts upon the armature wires through which the current is flowing (or, in the case of deeply-toothed armatures, on the protruding teeth): the second is that the revolving armature generates a counter electromotive force as its moving wires cut the magnetic lines.

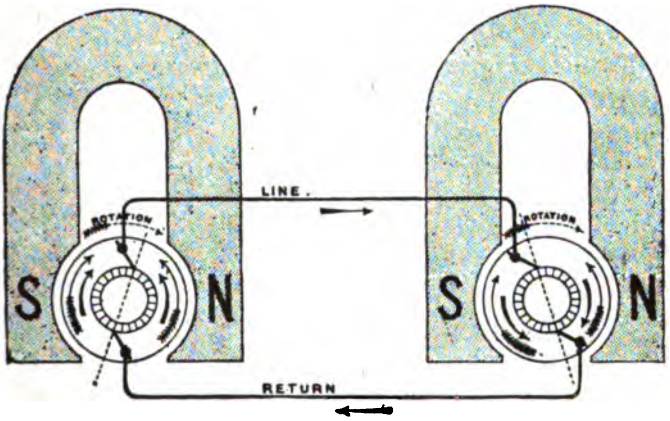
The Propelling Drag.—In Chapter V., on the mechanical actions in armatures, the drag, which a magnetic field exerts on a conductor carrying a current, has been explained, and calculations about its magnitude given. In a generator the drag acts in a direction which opposes the rotation, and is, in fact, a counter-force or reaction against the driving-force. In a motor the drag is the driving-force, and produces the rotation.

The Counter Electromotive-force.—Let it be remembered that wherever in an electric circuit, current flows through some portion of the circuit in which there is an electromotive-force, the current will there either receive or give up energy according to whether the electromotive-force acts *with* the current or *against* it. This will be made clearer by Fig. 368, representing a circuit in which there are a dynamo and a motor. Each is rotating right-handedly, and therefore generates an electromotive-force tending upwards from the lower brush to the higher. In each case the upper brush is the positive one. But in the dynamo, where energy is being supplied to the circuit, the electromotive-force is in the same direction as the current; whilst in the motor where work is being done, and energy is leaving the circuit, the electromotive-force is in a direction which opposes the current.

[1] *Annals of Electricity*, viii. 219, 1842, and *Scientific Papers*, p. 47.

There ought to be no difficulty in understanding that this electric reaction is an essential of motor working.

GENERATOR. FIG. 368. MOTOR.



We know that in the converse case, when we are employing mechanical power to generate currents by rotating a dynamo, directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately requires much more power to turn the dynamo than is the case when no electric work is being done. In other words, there is an opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive-force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive-force is a "counter electromotive-force."

The experiment of showing the existence of this counter electromotive-force is a very easy one. All one requires is a little motor, with a powerful field-magnet,[1] a few cells of battery of small internal resistance, and a galvanometer.

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[1] One of any ordinary type—a magneto-machine or a series-wound motor will answer.

They should be connected up in one circuit, and the deflexion of the galvanometer should be observed when the motor is held fast, and when it rotates with small and large loads. In an experiment made at the Technical College, Finsbury, on an Immisch motor, with separately-excited magnets, the following figures were obtained:—

Speed. Revs. per min.	*Current.* Amperes.	*Speed.* Revs. per min.	*Current.* Amperes.
0	20	160	7·8
50	16·2	180	6·1
100	12·2	195	5·1

Apparently, if the motor had been helped on to run at 261½ revolutions per minute, the current would have been reduced to zero. The current of 5·1 amperes was needed to drive the armature against friction at the speed of 195.

The existence of this counter electromotive-force is of the utmost importance in considering the action of the motor, because upon the existence and magnitude of this counter electromotive-force depends the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In fact, this counter electromotive-force is an absolute and necessary factor in the power of the motor, just as much as the velocity to which (*cæteris paribus*) it is proportional. Lieut. F. J. Sprague has made the suggestion to call it the "motor electromotive-force," thereby emphasizing the fact.

In discussing the dynamo as a generator, many considerations were pointed out, the observance of which would tend to improve the efficiency of such generators. It is needless to say that many of these considerations, such as the avoidance of useless resistances, unnecessary iron masses in cores, and the like, will also apply to motors. The freer a motor is from such objections, the more efficient will it be. But the efficiency of a motor in utilizing the energy of a current depends not only on its efficiency in itself, but on another consideration, namely the relation between the electromotive-force which it itself generates when rotating, and the electromotive-force or electric pressure at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive-force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive-force. A good low-pressure steam-engine does not become more "efficient" by being supplied with high-pressure steam. Nor can a high-pressure steam-engine, however well constructed, attain a high efficiency when worked with steam at low pressures. Analogous considerations apply to dynamos used as motors. They must be supplied with currents at electromotive-forces adapted to them. Even a perfect motor—one without friction or resistance of any kind—cannot give an "efficient" or economical result if the law of efficiency is not observed in the conditions under which the electric current is supplied to it.

ELEMENTARY THEORY OF ELECTRIC MOTIVE POWER.

It will be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current, depends upon the ratio between the counter electromotive-force developed in the armature of the motor and the electromotive-force of the current which is supplied by the battery. No motor ever succeeded in turning into useful work the whole of the currents that feed it, for it is impossible to construct machines devoid of resistance, and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the wires that offer the resistance. Let the symbol W stand for the electric power supplied to an electric circuit by a battery or dynamo acting as a source; and let w stand for that part of the energy which the motor takes up as useful power from the circuit.[1] These symbols may stand for the numbers of *watts* respectively supplied and utilized. All that part of the energy of the current which is not utilized by the motor, and transformed into useful work, will be wasted in useless heating of the resistances. The heat-loss will therefore be equal to $\mathrm{W} - w$.

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[1] The symbol w must be clearly understood to refer to the value of the work taken up by the motor, *as measured electrically*. The whole of this work will not appear as useful mechanical effect however, for part will be lost by mechanical friction, and part also in the wasteful production of eddy-currents in the moving parts of the motor. What proportion of w appears as useful mechanical work depends on the efficiency of the motor *per se*, which we are not here considering. In all that follows immediately we shall suppose such causes of loss not to exist, or the motor will be considered as a perfect motor.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, w must be as nearly as possible equal to W. It will be shown mathematically that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter electromotive-force of the motor and the whole electromotive-force of the battery that feeds the motor. (As it is not wished here to complicate general considerations by introducing into the expression for the efficiency the energy wasted in heat in the field-magnet coils of the motor, we here assume that the magnetism of the field-magnets is independently excited.) The proof will be given later. Let us call this whole electromotive-force with which the battery feeds the motor E, and let us call the counter electromotive-force E. Then the rule is

$$\frac{w}{\mathrm{W}} = \frac{\mathrm{E}}{E}.$$

But we may go one stage further. If the motor be prevented from turning, the current, as calculated by Ohm's law, would be

$$\mathrm{I} = \frac{E}{\mathrm{R}}.$$

If the resistances of the circuit are constant, the current i, observed when the motor is running, will be less than I. But, from Ohm's law, we know that

$$i = \frac{E - \mathrm{E}}{\mathrm{R}},$$

where R is the total resistance of the circuit. Hence

$$\frac{\mathrm{I} - i}{\mathrm{I}} = \frac{\mathrm{E}}{E} = \frac{w}{\mathrm{W}}.$$

From which it appears that we can calculate the efficiency at which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength. Now as this mathematical law of efficiency has been known for forty years, it is strange that, even in many of the accepted text-books, it was until lately ignored or misunderstood. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, has usually been given instead. A machine does not generally do its work with the best economy when it works furiously, performing the greatest work in the least possible time; and the maximum economy or efficiency of an electric motor is not when its output is at a maximum. Yet, strange to say, it was common ten years ago to find Jacobi's law of maximum power or activity stated as the law of maximum efficiency. Many electricians were consequently under the erroneous impression that a motor could never have a higher efficiency than 50 per cent.!

The true law of efficiency was clearly stated by Thomson in 1851, and is recognized in a paper by Joule at about the same date. See also Rankine's *Steam Engine*, p. 546. Professor Anthony, late of Cornell University, informs the author that he has taught the true law for the past fifteen years. Jacobi seems very clearly to have understood that his law was a law of maximum working, but not to have understood that it was not a law of true economical efficiency. In one passage, (*Annales de Chimie et de Physique*, t. xxxiv. 1852, p. 480), he says :—" Le travail mécanique maximum, *ou plutôt l'effet économique*, n'est nullement compliqué avec ce que M. Müller appelle les circonstances spécifiques des moteurs électro-magnétiques." Yet, though there is here apparently a confusion between the two very different laws, in a preceding part of the very same memoir Jacobi says (p. 466) :—" En divisant la quantité de travail par la dépense (de zinc), on obtient une expression très importante dans la mécanique industrielle: c'est l'effet économique, ou ce que les Anglais appellent *duty*." Here, again, is a singular confusion. The definition is perfect; but "effet économique" is not the same thing as the maximum power. Jacobi's law is not a law of maximum efficiency, but a law of maximum power; and that is where the error creeps in. It is significant, in suggesting the cause of this remarkable conflict of ideas, that throughout this memoir Jacobi speaks of *work* as being the product of force and velocity, not of force and displacement. The same mistake—common enough amongst continental writers—is to be found in the accounts of Jacobi's law given in Verdet's *Théorie Mécanique de la Chaleur*, in Müller's *Lehrbuch der Physik*, and even in Wiedemann's *Galvanismus.* Now the product of force and velocity is not work, but work divided by time, that is to say "power," or "rate of working," or "activity." This may account for the widely-spread fallacy. Jacobi makes another curious slip in the memoir above alluded to (p. 463), by supposing that the strength of the current can only become = 0 when the motor runs *at an infinite speed.* We all know now that the current will be reduced to zero when the counter electromotive-force of the motor equals that of the external supply; and if this is finite, the speed of the motor, if there is independent magnetism in its magnets, need also only be finite. This error—also to be found in Verdet—seems to have thrown the latter off the track of the true law of efficiency, and to have made him fall back on Jacobi's law. In a paper by Achard in the *Annales des Mines* in January 1879, a clear distinction is drawn between the maximum activity and the efficiency of a motor, and he points out how as the latter increases to a maximum, the former falls to zero. In April, Sir C. W. Siemens and Sir W. Thomson gave evidence on electric transmission before a Parliamentary Committee, the latter showing that it was possible to transmit 21,000 HP. through a copper wire ½-inch in diameter, to 300 miles, provided a potential of 80,000 volts was used. Later in the same year Professors Elihu Thomson and Houston, basing their remarks upon the suggestions of Sir W. Thomson and Siemens, proposed to obtain economic results by connecting in series several dynamos at one end of a line, and several motors at the other, so as to work with small currents and high electromotive-forces. The advantage of high voltage in both dynamo and motor at the two ends of the line was never better or more clearly put than by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association, in Sheffield in August 1879. These high voltages he proposed to obtain not by increasing the magnetism but by increasing the speed, and by separate excitation of both dynamo and motor. The gain in economy by allowing the motor to run at a high speed with efficiency increasing as its speed increases, was also pointed out by Dr. Werner von Siemens in his address to the Naturforscher meeting in September 1879 (see Werner von Siemens *Wissenschaftlichen und Technischen Arbeiten*, vol. ii., p. 374).

Jacobi's law concerning the maximum power of an electric motor supplied with currents from a source of given electromotive-force is the following:—The mechanical work given out by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter electromotive-force of the motor is equal to half the electromotive-force furnished by the battery or generator. Now, under these circumstances, only half the energy furnished by the external source is utilized, the other half being wasted in heating the circuit. If Jacobi's law was indeed the law of efficiency, no motor, however perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work.

Dr. Siemens, who first made us realize the true physical signification of the mathematical expressions which, until then, had been regarded as mere abstractions, showed, some years ago, that a dynamo can be, in practice, so used as to give out more than 50 per cent. of the energy of the current. It can, in fact, work more efficiently if it be not expected to do its work so quickly, while using so much current. In fact, if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before. Or, instead of gearing it up to run fast, we may gain the same advantage by strengthening its field-magnets.

Theory of Motors.—If $\mathcal{E}$ be the electromotive-force of the mains supplying the current to the motor when the motor is at rest, and i be the current which flows at any time, the whole electric power W expended in unit time will be expressed in watts, as the product of the whole of the applied volts multiplied by the whole of the amperes, or:—

$$\text{(Total watts) } \mathrm{W} = \mathcal{E}\, i = \mathcal{E}\,\frac{(\mathcal{E} - \mathrm{E})}{\mathrm{R}}. \qquad [\mathrm{I.}]$$

Now, when the motor is running, part of this electric power is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. The useful part may be similarly written down, as the product of the armature's own volts (the counter electromotive-force) and the amperes, or:—

$$\text{(Useful watts) } w = \mathrm{E}\, i = \mathrm{E}\,\frac{(\mathcal{E} - \mathrm{E})}{\mathrm{R}}. \qquad [\mathrm{II.}]$$

All the power which is not thus utilized is wasted in heating the resistances. So we may write:—

Power supplied = power utilized + power wasted in heating, or,

$$\mathrm{W} = w + \text{watts wasted in heating.}$$

But, by Joule's law, the heat-waste of the current whose strength is i running through resistance R, is expressed by the equation

$$= i^2\,\mathrm{R} \text{ (watts).}$$

Substituting this value above, we get

$$\mathrm{W} = w + i^2\,\mathrm{R},$$

Comparing equation [I.] with equation [II.], we get the following:—

$$\frac{w}{\mathrm{W}} = \frac{\mathrm{E}\,(\mathcal{E} - \mathrm{E})}{\mathcal{E}\,(\mathcal{E} - \mathrm{E})};$$

or, finally

$$\frac{w}{\mathrm{W}} = \frac{\mathrm{E}}{\mathcal{E}}. \qquad [\mathrm{III.}]$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its practical significance. We may appropriately call it *the law of Siemens.* Here the ration $\frac{w}{\mathrm{W}}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by so adjusting either the magnetism of the field-magnets or the speed of the motor that E is very nearly equal to E.

Now the power utilized is equal to the difference between the total power supplied and the part wasted in heat, or in symbols:—

$$w = E i - i^2 \mathrm{R}. \qquad \text{[IV.]}$$

In order to find what value of i will give us the maximum value for w (which is the work done by the motor *in unit time*), we must take the differential coefficient and equate it to zero.[1]

$$\frac{d w}{d i} = E - 2 i \mathrm{R} = 0,$$

whence we have

$$i = \tfrac{1}{2} \frac{E}{\mathrm{R}}.$$

But by Ohm's law, $\frac{E}{\mathrm{R}}$ is the value of the current when the motor stands still. So we see at once that, to get maximum work per second out of our motor, the motor must run at such a speed as to bring down the current to half the value which

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[1] The argument can be proven, though less simply, without the calculus as follows: write equation [IV.] in the following form:

$$i^2 \mathrm{R} - E i + w = 0.$$

Solving this as an ordinary quadratic equation, in which i is the unknown quantity, we have

$$i = \frac{E \pm \sqrt{E^2 - 4 \mathrm{R} w}}{2 \mathrm{R}}.$$

To find from this what value of i corresponds to the greatest value of w, it may be remembered that a negative quantity cannot have a square root, and that therefore the greatest value that w can possibly have will occur when

$$4 \mathrm{R} w = E^2,$$

for then the term under the root sign will vanish. When this condition is observed it will follow that

$$i = \frac{E}{2 \mathrm{R}},$$

or the current will be reduced to half its original value.

it would have if the motor were at rest. In fact, we here prove the law of Jacobi for the maximum rate of doing work. But here, since

$$i = \frac{E - \mathrm{E}}{\mathrm{R}} = \frac{1}{2}\frac{E}{\mathrm{R}},$$

it follows that

$$E - \mathrm{E} = \frac{1}{2}E,$$

or

$$\frac{\mathrm{E}}{E} = \frac{1}{2};$$

whence it follows also that

$$\frac{w}{\mathrm{W}} = \frac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.[1]

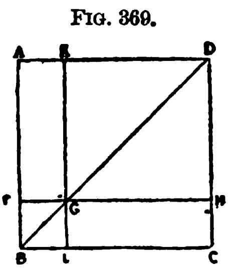
---

[1] It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Every one is familiar with the rule for grouping a battery which consists of a given number of cells, that they will yield a maximum current through a given external resistance when so grouped that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zinc of one's battery), is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in the heat of the cells, and half only will be available in the external circuit. If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will, of course, be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme case. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the rotating part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy the resistance of the armature should be very low as compared with that of the external circuit.

GRAPHIC REPRESENTATION OF LAWS OF MOTORS.

Several graphic constructions have been suggested to convey these facts to the eye; one of these enables us, in one diagram, to exhibit graphically both the law of maximum rate of working, and the law of efficiency.[1]

FIG. 369.



Let the vertical line, A B (Fig. 369), represent the electromotive-force E of the electric supply. On A B construct a square A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive-force E of the motor. The length of this quantity will increase as the velocity of the motor increases. Let E attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows:—Through F draw F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive-force at work in the machine producing a current is $E - \mathrm{E}$, which may be represented by any of the lines A F, K G, G H, or L C. Now the electric energy expended per second is $E i$; and since $i = \frac{E - \mathrm{E}}{\mathrm{R}}$, it may be written as

$$\frac{E(E - \mathrm{E})}{\mathrm{R}};$$

and the electric energy utilized by the motor, measured in *watts*, is

$$\frac{\mathrm{E}(E - \mathrm{E})}{\mathrm{R}}.$$

R being a constant, the values of the two may be written respectively

$$E(E - \mathrm{E}) \text{ and } \mathrm{E}(E - \mathrm{E}).$$

---

[1] See paper by the author in the *Philosophical Magazine*, Feb. 1883.

Now the area of the rectangle

$$\mathrm{A\ F\ H\ D} = E\,(E - \mathrm{E}),$$

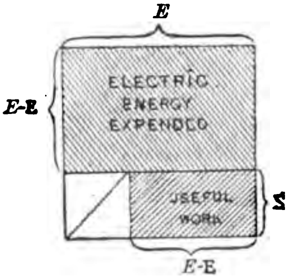
and that of the rectangle

$$\mathrm{G\ L\ C\ H} = \mathrm{E}\,(E - \mathrm{E}).$$

The ratio of these two areas on the diagram is the efficiency of a perfect motor, under the condition of a given constant electromotive-force in the electric supply.

Turn to Fig. 370, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter electromotive-force E is very small compared with *E*. Here the area which represents the energy expended, is very large; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

FIG. 370.



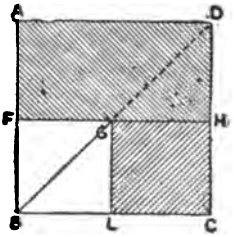
So far we have assumed that the efficiency of a motor (working with a given constant external electromotive-force) is to be measured electrically. But no motor actually converts into useful mechanical effect the whole of the electric energy which it absorbs, since part of the energy is wasted in friction and part in wasteful electro-magnetic reactions between the stationary and moving parts of the motor. What we are expressing thus as useful work is the work actually delivered to the armature to drive it. It is a mere matter of good engineering how small a percentage of this must be discounted for friction in the bearings, eddy-currents, hysteresis, and the like. If, however, we might consider the motor to be a *perfect* engine (devoid of friction, not producing wasteful eddy-currents, running without sound, giving no sparks at the collecting-brushes, &c.), then we might take the mechanical output as being precisely equal to the actual power delivered electrically to the armature. Such a "perfect" electric engine would, like the ideal "perfect" heat engine of Carnot, be perfectly reversible. In Carnot's heat engine it is supposed that the whole of the heat actually absorbed in the cycle of operations is converted into useful work; and in this case the efficiency is the ratio of the heat absorbed to the total heat expended. As is well known, this efficiency of the perfect heat engine can be expressed as a function of two absolute temperatures, namely, those respectively of the heater and of the refrigerator of the engine. Carnot's engine is also ideally reversible; that is to say, capable of reconverting mechanical work into heat.

The mathematical law of efficiency of a perfect electric engine illustrated in the above construction is an equally ideal case; and the efficiency can also be expressed, when the constants of the case are given, as a function of two electromotive-forces. We shall return to this comparison a little later.

The Law of Maximum Activity.

Let us next consider the area G L C H of the diagram (Fig. 371), which represents the work utilized in the motor. The value of this area will vary with the position of the point G, and will be a maximum when G is midway between B and D; for of all rectangles that can be inscribed in the triangle B C D, the square will have maximum area (Fig. 371). But if G is midway between B and D, the rectangle G L C H will be exactly half the area of the rectangle A F H D; or, the useful work is equal to half the energy expended. When this is the case, the counter electromotive-force reduces the current to half the strength it would have if the motor were at rest; which is Jacobi's law of the efficiency of a motor doing work at its greatest possible rate. Also F will be half-way between B and A, which signifies that $E = \frac{1}{2} E$.

FIG. 371.

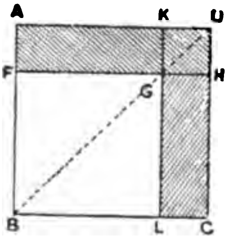


GEOMETRIC ILLUSTRATION OF JACOBI'S LAW OF MAXIMUM ACTIVITY.

Law of Maximum Efficiency.

Again, consider these two rectangles when the point G moves indefinitely near to D (Fig. 372). We know from common geometry that the rectangle G L C H is equal to the rectangle A F G K. The area (square) K G H D, which is the excess of A F H D over A F G K, represents therefore the electric energy which is wasted in heating the resistances of the motor. That the efficiency should be a maximum the heat-waste must be a minimum.

Fig. 372.



Geometric Illustration of the Law of Maximum Efficiency.

In Fig. 369 this corner square, which stands for the heat-waste, was enormous. In Fig. 371 it was exactly half the energy. In Fig. 372 it is only about one-eighth. Clearly, we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas G L C H and A F H D, which represents the efficiency, can therefore only become equal to unity when the square K G H D becomes indefinitely small—that is, when the motor runs so fast that its counter electromotive-force E differs from *E* by an indefinitely small quantity only.

It is also clear that if our diagram is to be drawn to represent any given efficiency (for example, an efficiency of 90 per cent.), then the point G must be taken so that area G L C H $= \frac{9}{10}$ area A F H D; or, G must be $\frac{9}{10}$ of the whole distance along from B towards D. This involves that E shall be equal to $\frac{9}{10}$ of *E*, or that the motor shall run so fast as to reduce the current to $\frac{1}{10}$ of what it would be if the motor were standing still. Thus we verify, geometrically, the law of maximum efficiency. If there is leakage in the line, then, as Professor Oliver Lodge and Mr. G. Kapp[1] have pointed out, this law will require modification, for the higher the counter electromotive-force of the motor, the higher will be the potential of the line and the greater the loss by leakage.

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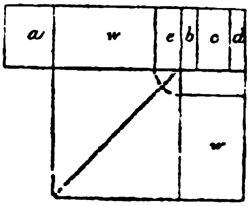
[1] See Kapp's *Electric Transmission of Energy* (1886), p. 165.

Further, if the motor be not a "perfect" one, but one whose intrinsic efficiency, or *efficiency per se*, is known, the actual mechanical work performed by the motor can be represented on the diagram by simply retrenching from the rectangle G L C H the fraction of work lost in friction, &c. Similarly, in the case where the electric energy expended has been generated in a dynamo-electric machine whose intrinsic efficiency is known, the total mechanical work expended can be represented by adding on to the area A F H D the proportion spent on useless friction, &c. To make the diagram still more expressive we may divide the area K G H D into slices proportional to the several resistances of the circuit; and the areas of these several slices will represent the heat wasted in the respective parts of the circuit. These points are exemplified in Fig. 373, which represents the transmission of power between two dynamos, each supposed to have an intrinsic efficiency of 80 per cent., each having 500 ohms resistance, working through a line of 1000 ohms resistance, the electromotive-force of the machine used as generator being 2400 volts, and the counter electromotive-force of the machine used as motor being 1600 volts.

FIG. 373.



The entire upper area represents the total mechanical work expended. Call this 100. It is expended as follows:— $a = 20$, lost by friction, &c., in the generator; $b = 6\frac{2}{3}$, lost in heating generator; $c = 13\frac{1}{3}$, lost in heating line-wires; $d = 6\frac{2}{3}$, lost in heating motor; $e = 10\frac{2}{3}$, lost in friction in the motor; $w = 42\frac{2}{3}$ is the percentage realized as useful mechanical work.

When the mechanical losses are thus taken into account it becomes evident at once that the maximum efficiency will be at some value of E less than *E*. This is considered further in Chapter XXVI. on the Transmission of Power.

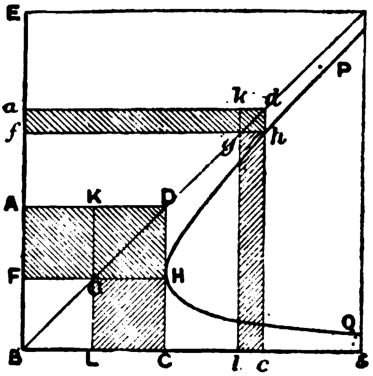
It is now evident what we have to do to obtain any desired percentage of efficiency. Suppose current is supplied at 100 volts at the mains: then to utilize 90 per cent., we must employ as motor a dynamo which, when running at its proper speed and output, generates an electromotive-force of 90 volts.

We may now extend the graphic method to two further cases. Suppose that E is no longer taken as a constant, but that the work to be done by the motor per second is a constant. For this case we may write equation [II.], p. 562, as

$$\mathrm{E}\,(E - \mathrm{E}) = w\,\mathrm{R}.$$

This equation is graphically represented by the curve P H Q (Fig. 374), in which the values of E are plotted as abscissæ and

FIG. 374.



those of E as ordinates. From this curve it is at once seen that there will be a certain minimum value of E which will suffice to give to the motor the prescribed amount of energy per second. The curve is so drawn that it passes through the corner H of all the areas equal to G L C H drawn to fit under the diagonal of the square. Of these areas, which represent equal work done by the motor, the one which has minimum value of E is the square which fits to the apex of the curve and corresponds to the case where $E = 2\,\mathrm{E}$. This result, which was first pointed out by Prof. Carhart,[1] is the converse of Jacobi's law, and, like it, involves an efficiency of only 50 per cent. A much higher efficiency is obtained when E and E are both greater, as indicated by the square drawn through the point *h*.

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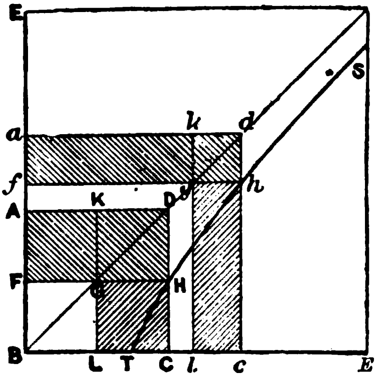
[1] *American Journal of Science*, xxxi. 95, 1886.

Again, suppose that W, the work supplied electrically, is maintained constant; for this case (Fig. 375) we may write equation [I.], p. 561, in the form

$$\mathit{E}\,(\mathit{E} - \mathrm{E}) = \mathrm{W}\ \mathrm{R},$$

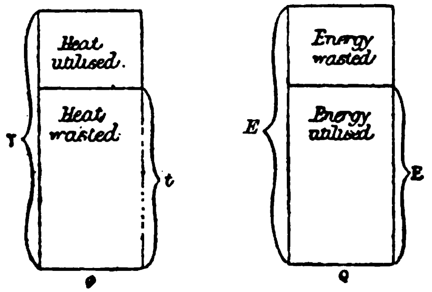
giving us the curve T H S. In this case E is a minimum when E is zero, and all the work is wasted in heat; and w, the work of the motor, is a maximum only when both E and E are infinitely great. This result is also due to Carhart.

FIG. 375.



It only remains to point out a curious contrast that presents itself between the efficiency of a perfect heat engine and that of a perfect electric engine. We saw that the one could be expressed as a function of two temperatures, whilst the other could be expressed as a function of two electromotive-forces.. But in the heat engine the efficiency is the greatest when the difference between the two temperatures is a maximum; whilst in the electric engine the efficiency is the greatest when the difference between the two electromotive forces is a minimum. The two cases are contrasted in Figs. 376 and 377, Fig. 376 showing the efficiency of a heat engine working between temperatures T and t (reckoned from absolute zero); whilst Fig. 377 shows the efficiency of an electric engine receiving current at an electromotive-force E, its counter electromotive-force being E. Joule's remark, here illustrated, that an electric engine may be readily made to be a far more efficient engine than any steam-engine, is amply justified by all experience. The rapid extension in the use of electric motors, large and small, which has taken place during the past few years, proves that where power can be produced sufficiently cheaply on the large scale, either from natural sources, such as water-power, or by large steam-engines burning cheap coal, such power can be electrically distributed to smaller motors (not exceeding a few horse-power) with an economic result; for the cost of erecting, maintaining, and supplying the electric power to such motors is less than the cost of erecting, maintaining, and supplying fuel and water to small steam-engines of equal power.

Fig. 376. Fig. 377.



HEAT ENGINE AND ELECTRIC ENGINE CONTRASTED.

SPEED AND TORQUE OF MOTORS.

Certain very important relations subsist between the condition of the electric supply and the speed and turning-moment of a motor.

In Chapter V., on Mechanical Actions and Reactions, it was set forth that the power transmitted along a shaft is the product of two factors, the speed and the torque (or turning-moment). If ω stands for the angular velocity and T for the torque,[1] then

$$\omega \, T = \text{mechanical work per second, or power.}$$

---

[1] If n be the number of revolutions per *second*, then $2 \pi n = \omega$. Also if F be the transmitted pull on the belt (or rather the difference between the pull in that part of the belt which is approaching the driving pulley and the pull in that part which is receding from the driving pulley) in pounds weight, and r be the radius of the pulley, $F r$ = the turning-moment or torque = T, then $\omega T = 2 \pi n r F$ = the number of foot-pounds per second transmitted by the belt. This may also be proved as follows: Horse-power is product

This may be expressed in watts by use of the proper coefficient.

Now if E is the electromotive-force generated by the armature, and i the current through it, the electric energy per second in the armature is the product;—

$$E\,i = \text{electric work per second (in watts}^{1}).$$

If the whole of these four quantities, ω, T, E, and i, are armature quantities, strictly, we may equate the electrical and mechanical expressions together; and the equation will be true for either a motor or a generator. In the generator, E and i are in the same direction and T opposes ω; or there is a counter-torque. In the motor, T and ω are in the same direction, but E opposes i; or there is a counter-electromotive-force.

In treating of the dynamo as a generator, it was assumed that the mechanical power could be supplied under one of the two standard conditions, on the one hand of *constant speed* (and torque varying with the electrical output), or else on the other (p. 130) of *constant torque* (and speed varying with the output). One of these two conditions being prescribed, algebraic expressions had then to be found for the two corresponding factors of the electric output, namely, the *electromotive force* and the current, under varying conditions of resistance in the circuit. Also we investigated these conditions which would result in making one or other factor of the

---

of the force into the velocity. The circumference of the pulley is $2\,\pi\,r$, and it turns n times per second, therefore the circumferential velocity is $2\,\pi\,r\,n$, and this, multiplied by F, gives the work per second. If F is expressed in grammes weight, and r in centimetres, then $2\,\pi\,r\,n\,F$ will give the power in gramme-centimetres, and must be divided by $7{\cdot}6 \times 10^6$ to bring it to horse-power, and must be multiplied by 981×10^{-7} to bring it to watts. If ω is in radians per second and T in centimetre-dynes, then the product will be in ergs per second, and can be brought to watts by dividing by 10^7.

[1] Since 1 volt $= 10^8$ C.G.S. units of electromotive-force, and 1 ampere $= 10^{-1}$ C.G.S.units of current, 1 watt (or volt-ampere) will be $= 10^7$ C.G.S.units of work per second $= 10^7$ ergs per second $= 10^7 \div 981$ gramme-centimetres per second.

electric output constant. It was found convenient to study the relation between the two factors of output by the aid of the curves known as *characteristics.*

Similarly, in treating the dynamo as a motor, it will be assumed that such arrangements of electric supply can be made that the electric power can be furnished under one of the two standard conditions, on the one hand of *constant potential* (and current varying with the mechanical output of the motor), or on the other of *constant current* (and potential varying with the mechanical output). One of these two conditions being prescribed, we shall then have to find algebraic expressions for the two corresponding factors of the mechanical output, namely, the *speed* and the *torque*, under varying conditions of load on the shaft. Also, we shall investigate what are the conditions which will result in making one or other factor of the mechanical output constant: in other words, we shall ascertain what are the conditions of self-regulation to make the motor run at constant speed or with constant torque. Lastly, it will be found convenient to study the relation between speed and torque by the aid of curves, which, by analogy, we may call *mechanical characteristics.*

GENERAL EXPRESSIONS FOR TORQUE AND SPEED.

The work imparted per second to the shaft of the motor may be expressed either in electrical or mechanical measure. In the former case it is the product of the motor's electromotive-force (i. e., the counter electromotive-force opposing the electromotive-force of supply) into the current flowing through the armature; in the latter case it is the product of angular speed into torque. So we may write

$$w = \mathrm{E}\, i_a = \omega\, \mathrm{T} = 2\, \pi\, n\, \mathrm{T};$$

and (average) $\mathrm{E} = n\, \mathrm{C}\, \mathbf{N}$ exactly as in a dynamo that is being used as a generator (see p. 211). Hence

$$2\, \pi\, n\, \mathrm{T} = n\, \mathrm{C}\, \mathbf{N}\, i_a,$$
$$2\, \pi\, \mathrm{T} = \mathrm{C}\, \mathbf{N}\, i_a;$$

and finally the average value of the torque will be

$$T = i_a \frac{C\,\mathbf{N}}{2\,\pi} \quad . \; . \; . \; . \; . \; . \; . \quad [\alpha].$$

From this it appears that if $\mathbf{N}$ is constant, the torque is simply proportional to the current in the armature.

To develop this expression further, we must remember that i can be calculated in terms of the electromotive-force of supply E, as measured at the terminals of the machine, and the internal resistance of the circuit through the armature part, which we call r; and then

$$i_a = \frac{E - \mathrm{E}}{r};$$

whence it follows that

$$T = \frac{C\,\mathbf{N}}{2\,\pi} \cdot \frac{E - n\,C\,\mathbf{N}}{r} \quad . \; . \; . \quad [\beta].$$

From this it follows that when the speed becomes so great that $n\,C\,\mathbf{N} = E$, there will be no torque. In fact, when there is no resisting force on the shaft the motor runs empty at its highest speed, namely, such as will make the counter electromotive-force as nearly as possible equal to the electromotive-force of supply. The maximum value of T, supposing $\mathbf{N}$ constant, is obviously when $n = 0$.

An expression for the speed can be obtained from the preceding:

$$2\,\pi\,T\,r = C\,\mathbf{N}\,E - n\,C^2\,\mathbf{N}^2;$$

$$n = \frac{E}{C\,\mathbf{N}} - \frac{2\,\pi\,T\,r}{C^2\,\mathbf{N}^2} \quad . \; . \; . \quad [\gamma].$$

In equation [α] T will be expressed in dyne-centimetres if i_a is in absolute units of current (see p. 18); if i_a is given in amperes, then the value must be divided by 10 if T is to be obtained in dyne-centimetres, or by 9810 if it is to be obtained in gramme-centimetres, or by 13·56 × 10^7 if the torque is to be expressed in pound-feet (*i. e.* so many pounds weight acting at a radius of one foot).

In equation [γ], in order that n may be expressed in revolutions per second, the value of E, if given in volts, must be multiplied by 10^8; that of r, if in ohms, by 10^9; whilst T must be reduced to dyne-centimetres. If T is given in pound-feet, its value must be multiplied by 1·356 × 10^7.

[Examples:—(1) In one of Brown's 4-pole machines used as motor C = 368; $i_a = 275$; giving 250 HP. at 500 revs. per minute. Calculate the number of magnetic lines that must go through the armature. (2) A 2-pole motor is required to supply 4 HP. in an arc-light circuit in which the current is kept at 10 amperes: How many volts must it generate? Assume **N** = 2,000,000, and that the speed is 15 revs. per second, how many armature conductors must it have?]

[The three equations [α], [β], and [γ] are true, not only for motors, but for generators, the *E* of the formulæ being in the latter case replaced by *e*. This will give negative values for T, the significance of the sign being that the torque due to the action of the magnetic field on the conductors carrying the armature current is such as to oppose the driving.]

It will be noticed that if only *r* is very small, and **N** relatively very large, the second term may be neglected, and the speed will then depend on the first term only. It will be the smaller as **N** is greater: this being the simple converse of the corresponding fact that the more powerful the magnetic field the less need be the speed of the dynamo to give the desired output. We may also notice that if **N** is constant, the speed is proportional to *E*: it will be constant if the condition of supply is that of constant potential, but will be variable if *E* varies. Another important point is that, if a motor is to do its work at a slow speed, C should be great as well as **N**.

We must next inquire how *n* and T are affected by the fact that the value of **N** depends upon the construction and winding of the field-magnet of the motor, and by the conditions of supply. We shall consider the following kinds of machine:—

A. *Magneto Motor* and *Separately-excited Motor.*
B. *Series-wound Motor.*
C. *Shunt-wound Motor.*
D. *Compound-wound Motor.*

In each instance we shall have to take into account the conditions of supply, according as *E* or *i* is constant.

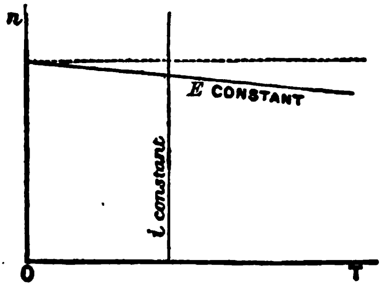
MAGNETO MOTOR AND SEPARATELY-EXCITED MOTOR.

It is here assumed that $\mathbf{N}$ is constant, in other words, that the perturbing reactions of the armature may be neglected. This will only be true when the lead at brushes is nearly zero, and the field-magnet powerful. Under these circumstances the general formulæ already found require small modification. The only internal resistance is that of the armature r_a.

Case (i.) : *E constant.*

In this case formula [γ] gives the desired relation, from which the *mechanical characteristic* may be plotted out, as in Fig. 378. It is a straight line cutting the axis of n at a point representing to scale that speed at which $n \text{ C } \mathbf{N} = E$; and it slopes downwards at an angle such that the tangent of the slope is equal to $2 \pi r_a \div \text{C}^2 \mathbf{N}^2$, or is proportional to the internal resistance. In the case of the separately excited motor, increase in the exciting current, strengthening the field, will obviously make the sloping line more nearly horizontal, as well as lowering the speed as a whole.

FIG. 378.



MECHANICAL CHARACTERISTICS OF MAGNETO MOTOR.

If we attempt to take into account the reactions of the armature, we must remember that the effect of the armature current is to demagnetize, if there is a backward lead, and to magnetize if there is a forward lead. A backward lead, then, would tend to make the sloping line, at constant E, rise and become more level as the torque increased, because it would weaken the magnet, and so let the speed increase; whilst a forward lead would tend to make it slope still more.

Practical Determination of the Proper Potential for Given Motor.

Suppose a motor having a certain steel magnet and a certain armature be given, and let it be required to determine the potential at which it will give a certain speed. Run the motor on open circuit as a generator at the given speed, and observe the potential at its terminals. That is the number of volts E with which it must be supplied.

Case (ii.): i *constant.*

In this case as reference to formula [a] shows, the torque is constant, being independent of speed and of internal resistance. The mechanical characteristic of the machine under these conditions is a vertical straight line.

SERIES MOTOR.

The fundamental equations are as before, with the addition of the following:—

$$r = r_a + r_m;$$

but now we may with advantage introduce the approximate formula for the law of the electromagnet (derived from Frölich's) given in Chapter VI., and write, as on p. 166, where i' is the diacritical current,

$$\mathbf{N} = \overline{\mathbf{N}} \frac{i}{i + i'}.$$

Putting this value of $\mathbf{N}$ into the expression [a], on p. 567, for the torque, and writing for brevity $\frac{C\overline{\mathbf{N}}}{2\pi} = \mathrm{Y}$, we have

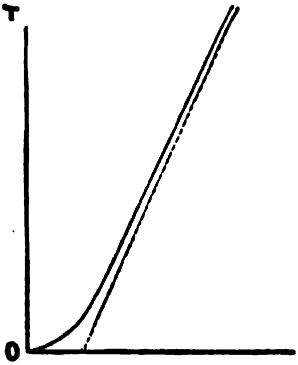
$$\mathrm{T} = \mathrm{Y} \frac{i^2}{i + i'}.$$

This relation between torque and current is given graphically in Fig. 379. For values of i that are small as compared with

i', T varies nearly as i^2; whilst for large values of i, as magnetic saturation advances, T is nearly proportional to i. The equation may also be written in the quadratic form

$$i^2 - \frac{T}{Y}\,i - \frac{T}{Y}\,i' = 0,$$

Fig. 879.



the solution of which is

$$i = \frac{T}{2\,Y}\left\{ 1 \pm \sqrt{1 + \frac{4\,Y}{T}\,i'} \right\}$$

Now from the expression given above we have

$$n = \frac{E\,i}{2\,\pi\,T} - \frac{r\,i^2}{2\,\pi\,T};$$

$$n = \frac{E\,i}{2\,\pi\,T} - \frac{r\,(i + i')}{2\,\pi\,Y};$$

and inserting the value of i as above

$$n = \frac{E}{4\,\pi\,Y}\left\{1 + \sqrt{1 + \frac{4\,Y}{T}\,i'}\right\} - \frac{r\,T}{4\,\pi\,Y^2}\left\{1 + \sqrt{1 + \frac{4\,Y}{T}\,i'}\right\} - \frac{r\,i'}{2\,\pi\,Y}$$

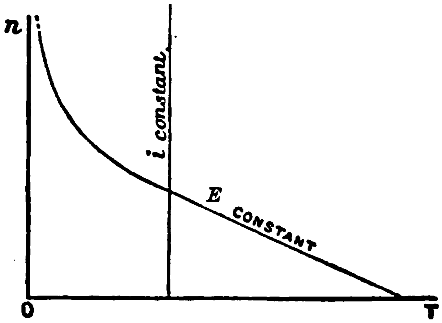
To simplify this hyperbolic expression, it is permissible for large values of T to neglect the second term under the root sign, giving approximately,

$$n = \frac{E - r\,i'}{2\,\pi\,Y} - \frac{r\,T}{4\,\pi\,Y^2}.$$

Case (*i.*) : *E constant.*

If E is constant, then, as the last equation shows, for large values of T the values of n are equal to a certain constant less a quantity proportional to T; or the mechanical characteristic at this point (when the magnets are well saturated) is, for all large values of T, approximately a straight line as shown in Fig. 380.

FIG. 380.



MECHANICAL CHARACTERISTICS OF SERIES MOTOR.

Case (ii.): *i constant.*

Here, clearly, saving for secondary effects, the magnetization will be constant; hence the torque will also be constant, as in Fig. 380. With a load exceeding a certain amount, the motor will not start; with a lesser load it will race until friction and eddy-currents make up the difference.

The properties of series-wound motors are so important that we may pause to consider them a little more fully. We know that if the current running through a series dynamo be constant, so that its magnetism is constant, the electromotive-force it develops is almost exactly proportional to its speed. It therefore follows that if E is proportional to ω, T will be proportional to i. This is abundantly verified in the case of series motors by experiments. When a Siemens series dynamo was arranged to lift a load of 56 lbs. on a hoist, is lifted this load at the rate of 212 feet per minute, developing a counter electromotive-force of 108·81 volts. The applied electromotive-force was 111 volts, and the resistance of the circuit was 0·3 ohm. The effective electromotive-force was therefore 2·19 volts and the current 7·3 amperes. When the resistance of the circuit was increased to 2·2 ohms, the speed fell to 169 feet per minute, the counter electromotive-force to 94·94; the effective electromotive-force, E – E, was therefore 16·06 volts, and the current 7·3 amperes as before. When 4·8 ohms were inserted, the speed fell to 141 feet per minute, and E to 76 volts; E – E was 35 volts, and the current 7·3 amperes as before. *With the same load, the same current*, whatever the speed. The figures given on p. 556, relative to the Immisch motor also illustrate this point. The speed of a given series-wound motor depends solely on the electromotive force of the generator and on the resistance of the circuit.

The fact that the torque of a series motor depends only on the current is of advantage in the application of motors to propulsion of vehicles (such as tram-cars) which at starting require for a few seconds a power greatly in excess of that needed when running.[1] To start, a large current must be turned on. One convenient way of arranging this is to use two motors, coupled habitually in series. When starting, they are, by moving a commutator, coupled in parallel. This doubles the electromotive-force for each, and at the same time halves the resistance. For a few seconds a very strong current flows—much stronger than that which the motors would stand for any prolonged work—and so provides the needful additional torque.

In the series motor, when supplied at constant potential, E is not proportional to the speed, because the field-magnetism is not constant, but falls off as E increases, being (if unsaturated) nearly proportional to E – E. It therefore will not run at a constant speed. Neither will it run at a constant speed if supplied with a constant current.

Use of two Series Motors in Transmission.—It is known that if two similarly-constructed series wound machines are used—one as generator, the other as motor—the arrangement is almost perfectly self-regulating, the speed of the motor at the receiving end being almost constant if that of the dynamo at the transmitting end is constant. Every addition to the load put upon the motor, tending to check the speed, causes an increase of current to flow, and so throws a proportionate additional work upon the generator, which in turn takes more power from the steam engine to keep up its speed. As we have shown above, the torque of the motor T_2 will depend, in the given machine, on the current alone, and on the current will depend the torque at the dynamo T_1. Mr. Kapp has further shown[1] how, if there is a resistance in the line, the arrangement may still be made self-regulating by choosing as generator and motor two machines so wound that, comparing their characteristics for the prescribed speeds, the difference in their electromotive-forces corresponding to a given value of current shall be equal to the electromotive-force requisite to drive that particular current through the resistance in the whole circuit. Some further particulars of series machines are given in Chapter XXVI., on Transmission of Power.

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[1] See remarks by E. Hopkinson, *Proc, Inst. Civil Engineers*, xci. pt. i. 6, 1887.

The late Sir C. W. Siemens[2] drew attention in 1880 to the singular properties of the combination of a generating dynamo and a magneto motor, instancing a locomotive motor which, when descending an incline, quickens its speed and actually becomes a generator of currents, paying back the spare power into store. He also remarked how two trains driven by motors running on the same pair of electric rails, tend to regulate one another, the one on a descending portion of the road transmitting power to the other, as though "connected by means of an invisible rope."

SHUNT MOTOR.

The fundamental conditions are as follows:—

$$T = i_a \frac{C N}{2 \pi};$$

$$i_a = i - i_s ;$$

---

[1] See Kapp's *Electric Transmission of Energy*, p. 176.

[2] *Journal Soc. Telegr. Engineers*, ix. 301, 1880.

and, adopting the appropriate form for the law of magnetization from p. 167.

$$\mathbf{N} = \bar{\mathbf{N}} \frac{E}{E + E'} ;$$

$$\mathrm{E} = E\left(1 + \frac{r_a}{r_s}\right) - r_a i.$$

[illegible]

From the first three of these we get

$$\mathrm{T} = \frac{\mathrm{C}}{2\pi}\left(i - \frac{E}{r_s}\right) \bar{\mathbf{N}} \frac{E}{E + E'} ;$$

and, transposing and writing Y for C $\bar{\mathbf{N}} \div 2\pi$,

$$i = \frac{\mathrm{T}}{\mathrm{Y}} \cdot \frac{E + E'}{E} + \frac{E}{r_s} ;$$

and from the last of the four

$$n = \frac{1}{\mathrm{C}\,\mathbf{N}} \left\{ E\left(1 + \frac{r_a}{r_s}\right) - r_a\, i \right\}.$$

Inserting the value of *i*, we have

$$n = \frac{E + E'}{2\pi \mathrm{Y}} \left\{ 1 + 2\frac{r_a}{r_s} - \frac{r_a \mathrm{T}}{\mathrm{Y}} \cdot \frac{E + E'}{E^2} \right\}.$$

Case (i.) : *E constant.*

The last equation shows that a shunt-motor, supplied at constant potential, will have a speed that would be constant and independent of the torque if it were not for internal resistance; and further, that the consequent falling off as the torque increases will be the less as the field-magnetism is the more powerful.

As an example, a Victoria shunt motor tested by Mr. Mordey, in which the load was varied from 91·8 × 10^7 to 1357·2 × 10^7 dyne-centimetres, only decreased its speed from 16·25 to 15·75 revolutions per second.

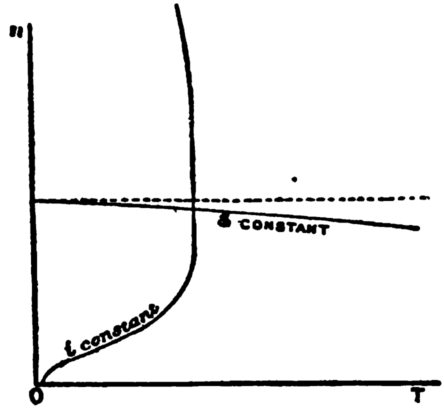
It is instructive to contrast the self-regulating power of a shunt dynamo with the self-governing power of a shunt motor. The former, when driven at a constant speed, generates electric power at a nearly constant potential; the latter, when supplied from the mains at a constant potential, would furnish mechanical power at a nearly constant speed; and in both cases the departure from absolute constancy is proportional to the internal resistance of the armature coils, and to the output, electrical or mechanical, of the machine for the time being.

So far we have supposed the armature to exert no magnetic reaction. Now, as we shall see, to obtain sparkless running there must be a backward lead, and in motors a backward lead tends to demagnetize. But demagnetizing tends, as we have seen, to increase the speed; hence in the case of constant-pressure supply, when there is a great load, the very reaction of the great current will tend to prevent the speed from falling, making the shunt-motor very nearly self-regulating. These reactions must now be considered in detail.

Case (ii.): *i constant.*

The determination of this case is more complicated, though the general considerations are simple enough. If the motor

FIG. 381.



MECHANICAL CHARACTERISTICS OF SHUNT MOTOR.

is standing still when the current is turned on, nearly all the current will go through the armature, next to none through the shunt; hence there will be little magnetism, and therefore almost no torque. Such a machine will not start itself with any load on; but if it be once started, its counter electromotive-force will cause the current in the armature to decrease, whilst that round the shunt increases. The torque will therefore then increase with the speed, but not indefinitely, for as the magnetism advances in its degree of saturation, the increase of N will no longer compensate for the decrease of i_a; and from that point onwards the torque will decrease if the speed is allowed to increase. And, hypothetically, the speed should increase until the motor's own electromotive-force exactly equals the difference of potentials due to the whole of the constant current flowing through the resistance of the shunt, under which circumstances there will be no current through the armature and zero torque. Fig. 381, which, like the preceding, is taken from Dr. Frölich's work, gives the mechanical characteristics for the two cases.

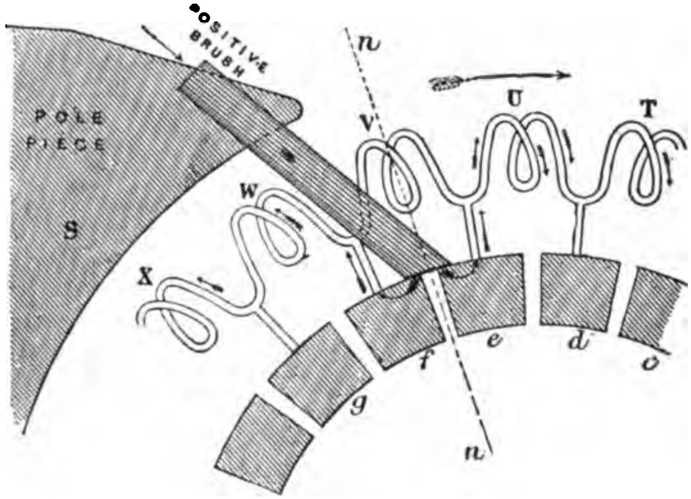
REACTION BETWEEN ARMATURE AND FIELD-MAGNETS IN A MOTOR.

In Chapter IV., pp. 62 to 103, the reactions between the armature and field-magnets of a dynamo were considered in detail, but attention was confined solely to that which occurs when the dynamo is used as a generator. In that case the current induced in the armature coils tended to magnetize the armature core in a direction nearly at right angles to the direction in which the field-magnets magnetized it, and in consequence there was a resultant magnetization at an oblique angle. This obliquity compelled a certain angular lead to be given to the brushes in the sense of the rotation; and the necessary result of the forward lead of the brushes was to cause the armature current to tend partially to demagnetize the field-magnets. Reference to Fig. 59, p. 76, will show that wherever the brushes are placed there is a tendency to form corresponding poles, and these armature poles tend to produce in the iron pole-piece of the field-magnets an opposite polarity to their own, and therefore to weaken or strengthen the field according to the lead. The same thing is true of a motor; but with a difference. A current supplied from an external source magnetizes the armature and makes it into a powerful magnet, whose poles would lie, as in the dynamo, nearly at right angles to the line joining the pole-pieces, were it not for the fact that in this case also a lead has to be given to the brushes. Suppose, as in most of the drawings in this book, that the S pole of the field-magnets is on the left, and the N pole on the right. Also that the current so traversed the armature that it caused the highest point to be a S pole and the lowest point a N pole. This means that if the armature is wound right-handedly the current must come in through the top brush and leave by the bottom one, the top brush being connected to the + main. Compare with p. 64. Clearly, in this case, the armature will rotate right-handedly, because the S pole at the top will be repelled from the S pole on the left and attracted toward the N pole on the right. It will therefore run right-handedly (in a right-hand field) when the current flows downwards from top to bottom, exactly as the armature of a generator must run in order to send a current upwards. In each case the direction of the induced electromotive-force is the same—upwards—*with* the current in the dynamo, *against* the current in the motor.

It follows that a forward lead would convert the cross magnetizing-force into one that tends to increase that of the field-magnet, whilst a backward lead tends to demagnetize. Further, since with a forward lead the armature polarity strengthens that of the field-magnet, it is possible for a motor to be worked without any other means being taken to magnetize the field-magnets, the armature will induce a pole in the field-magnet and then attract itself round towards this induced pole. This principle has been used for many years in small motors, having been apparently first applied by Wheatstone.

The cross-magnetizing force will also have the effect of weakening the field under the two leading pole-tips, and of strengthening them under the two trailing pole-tips. This is the opposite effect to that in a dynamo. In the motor (without lead even) the cross-magnetizing reaction tends to shift round the field in a sense *opposite* to that of the rotation. We shall now see what are the conditions for minimum sparking. Consider (Fig. 382) a coil W ascending on the left. The current in it is descending from the top brush, whilst it is itself the seat of an electromotive force that tends to stop or reverse its current. Now we know that the condition of non-sparking requires that at the moment whilst the coil passes under the brush, and is short-circuited, it should be passing through a field that is not only sufficiently strong, but one that tends to reverse the direction of its current. It is already in such a field; hence the act of commutation must take place *before* it passes out of this magnetic field. It must be commuted before it arrives at the highest point. In other words, a backward displacement must be given to the brushes if there is to be no sparking. The neutral line $n\ n'$ will therefore rake *backwards* in a motor into the fringe of the magnetic field. But since (in every case) both eddy-currents and

FIG. 382



THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A MOTOR.

hysteresis tend to shift the magnetic field slightly in the direction of the rotation—increasing the lead in a generator, diminishing it in a motor—it follows that the negative (or backward) lead in a motor may be slightly less than the positive (or forward) lead in a generator, for equal flow of current and equal excitation.[1] The advantage in point of weight of a motor in which the armature should help to excite the field-magnets, thereby reducing the power and weight of the latter, led Professors Ayrton and Perry,[2] in 1883, to advocate designs with weak field-magnets and powerful armatures acting with a forward lead. But from the foregoing considerations it follows that if a forward lead is given to the brushes of a motor in order to get a more powerful rotation, the motor will inevitably spark at the brushes. The fascinating notion of using the armature to magnetize has proved a failure in practice. With a forward lead the motive power relatively to weight would be undoubtedly larger than with a backward lead, but it is accompanied by destructive sparking. Minimum of sparking may be reconciled with high efficiency, but only by one way. That way is to design and construct motors so that the armature shall not perturb the magnetic field due to the field-magnets. This can be accomplished by following out the very same principles of design and construction which were found to be correct guides in the case of dynamos used as generators. *The field-magnets must be made very powerful in proportion to the armature.* If they are, then there will be no perturbations, no obliquity in the resultant magnetic field, no lead to the brushes, and no sparking. Only in a few cases when minimum weight is of more importance than high efficiency, can this rule be departed from, and then it becomes necessary to take special means, such as providing auxiliary poles, or specially shaped pole-pieces, to prevent the sparking which would follow from having small or weak field-magnets.

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[1] This appears to be the explanation of the differences—otherwise unimportant—observed by Snell; *Journal Inst. Electr. Engineers*, xix. 194, 1890.

[2] *Journal Soc. Telegr. Engineers*, xii., May, 1883.

Mr. Mordey,[1] who has carefully tracked out the analogies between dynamos and motors, has observed that in several respects it is even more important that the rules laid down for the good design of generators should be observed for motors. Eddy-currents must be even more carefully eliminated. Also the greatest attention must be paid to proper mechanical arrangements for transmitting to the shaft the forces that are thrown by the magnetic field upon the conducting wires around. See Chapter XIII.

Consider the conditions which are bound up in the disposition of the magnetic fields of the generator and the motor respectively. In one the armature is mechanically driven round while the magnetic forces in the field tend to pull it back. In the other, the magnetic forces of the field tend to drag it round, and it is thereby enabled to do mechanical work. In one case there is an opposing mechanical reaction tending to stop the steam-engine. In the other there is set up an opposing electrical reaction (the induced counter electromotive-force) tending to stop the current.[2] In both cases the rotation is supposed to be taking place in the same sense—right-handedly. In both the effect is to displace the lines of force of the field, but in the generator the mechanical rotation acts as if it dragged the magnetism round, whilst in the motor the reciprocal magnetic reactions act as if they tried to drag round the armature, producing mechanical rotation. In the generator we found that the effect of self-induction in the armature was to require a positive lead. In the motor, on the contrary, the effect of self-induction is to necessitate a negative lead. If a motor is set with no lead, and if the field-magnets are very weak or are not excited at all, it will run in either direction according as it may be started.

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[1] *Phil. Mag.*, Jan. 1886.

[2] The law of the electrical reaction resulting in a generator from the mechanical motion is summed up in the well-known law of Lenz, that *the induced current is always such that by virtue of its electro-magnetic effect it tends to stop the motion that generated it.* In the converse case of the mechanical reaction resulting, in a motor, from the flow of electric energy, it is easy to formulate a converse law, viz., that *the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current.*

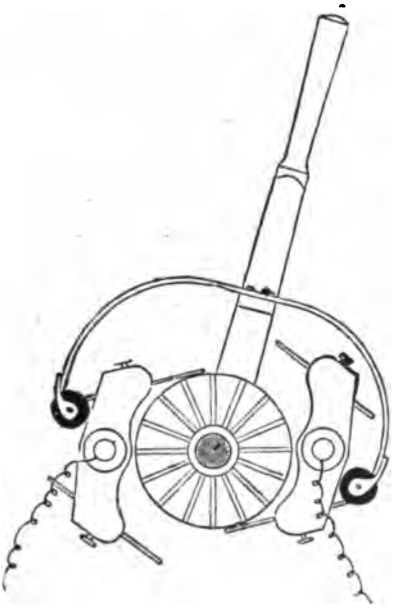
If in a motor with well-excited field-magnet the current be reversed in the *armature part* of the circuit only, the motor will usually reverse its rotation, but will usually require the lead to be reversed to run as sparklessly as before. If, instead of reversing the current in the armature, the magnetism of the field-magnet be reversed, a similar result will follow. If both are reversed at the same time, the motor will go on rotating as if nothing had happened.

Dynamos wound and connected for working as generators of continuous currents may be used in all cases as motors, but with some difference. A series dynamo set to generate currents when run right-handedly (and therefore having a forward right-handed lead), will, when supplied with a current from an external source, run as a motor, but runs left-handedly against its brushes. To set it right for motor purposes requires *either* that the connexions of the armature should be reversed, *or* that those of the field-magnet should be reversed (in either of which cases it will run right-handedly), *or* else the brushes must be reversed and given a lead in the other direction (in which case it will run left-handedly). A shunt dynamo set ready to work as a generator will, when supplied with current, run as a motor in the same direction as it ran as a generator; for if the current in the armature part is in the same direction as before, that in the shunt is reversed, and *vice versâ*. A compound-wound dynamo, set right to run as a generator will run as a motor in the reverse sense, against its brushes if the series part be more powerful than the shunt, and with its brushes if the shunt part be the more powerful. If the connexions are such (as in compound dynamos) that the field-magnet receives the sum of the effects of the shunt and series windings when used as a generator, then it will receive the difference between them when used as a motor. There are certain advantages in using a differentially-wound motor, as will appear hereafter.

The subject of alternate-current machines as motors is treated separately in Chapter XXIV.

Reversing Gear for Motors.—A motor, as will be seen from the preceding discussion, can be reversed by the operation of reversing the current through the armature, and at the same moment reversing the lead. But reversing the current can also be accomplished by rotating the brushes through 180°. Consequently, both these actions may be accomplished by the single operation of advancing the brushes through $180° - 2\,\phi$, where ϕ is the original angle of lead. But as the brush would then slant in the wrong direction, it is better to provide a second set of brushes. This is, indeed, Hopkinson's method of reversing. He employs two pairs of brushes, each pair being capable of moving about a common pivot, so that either the pair having a lead in one direction or the pair having a lead in the other direction can be let down upon the collector. A reversing gear, designed by Mr. A. Reckenzaun for the motors of the launch *Electricity*, is shown in Fig. 383. In it there are two pairs of brushes; the two upper are fixed to a common brush-holder, which turns on a pivot, and can be

Fig. 383.



Reversing Gear for Electric Motor.

tilted by pressing a lever handle to right or to left. The two lower brushes are also fixed to a holder. Against each brush-holder presses a little ebonite roller, at the end of a bent steel spring, fixed at its middle to the handle. The result of this arrangment is that, by moving the lever, the brushes can be made to give a lead in either direction, and so starting the motor rotating in either direction. Such a reversing gear is obviously a most useful adjunct for industrial applications of motors, and if the difficulties of sparking at the brushes caused by the sudden removals of them from the collector be obviated, must prove much better than any mechanical device to reverse the motion by transferring it from the axle of the motors through a train of gearing to some other axle. One great advantage of electric motors is, that they can be easily fixed directly on the spindle of the machine which they are to drive; an advantage not lightly to be thrown away.

Another form of reversing gear has been designed by Professors Ayrton and Perry. It consists of a double collar upon the spindle of the motor; in one, the inner collar, having a pin fitting into a spiral groove in the spindle, and being free to move relatively to the spindle. Any displacement along the spindle given to the inner collar through the outer one causes the pin in the former to move along the groove, and the collar rotates through a certain angle. This collar, in Ayrton and Perry's motor, carries the brush-holders, and therefore by rotating alters the lead. Motors fitted with this gear were depicted in earlier editions of this work. Other forms of reversing gear for small motors have been designed by the author, who cuts the segments of the collector or commutator spirally, and therefore obtains a change of lead by simply sliding the brushes forward or backward parallel to the axle of the motor.

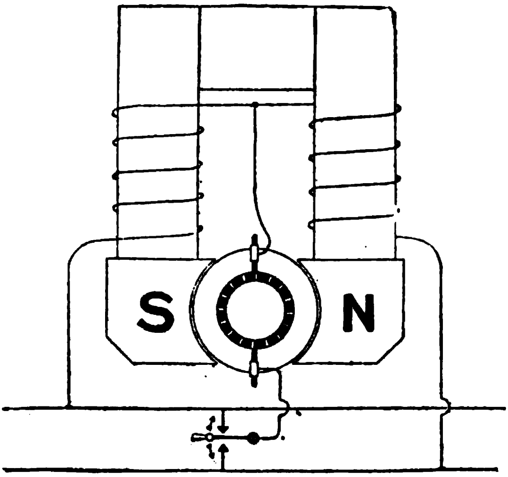
In Reckenzaun's motor the reversing gear consists of two pairs of brushes which are mounted so as to slide on guides or ways; reversal being accomplished by shifting a lever which slides forward one pair whilst it draws the other pair back.

It is also theoretically possible to construct a motor which shall reverse by simply reversing the current in the armature part; for this end the pole-pieces must be so shaped that when no angular lead is given to the brushes, the angle between the diameter of commutation and the effective pole in the pole-piece shall be that required for steady running. If this can be found, then merely reversing the polarity of either part will reverse the motor.

If the field-magnets of a motor are so powerful relatively to the armature that no lead has to be given to the brushes, the rotation can be reversed by reversing the polarity of either part. In Immisch's larger motors, the reversing gear, which is very substantial, removes one pair of brushes and puts down at the same diametral points a second pair, reversed in position and polarity.

The form of brush shown in Fig. 276 *c*, p. 381, is designed by Holroyd Smith for motor work, as it allows of rotation in either direction. So also do carbon-brushes, such as Fig. 277, p. 382.

FIG. 384.



ELECTRIC REVERSING GEAR FOR A MOTOR.

Another mode of reversing was suggested by the author[1] in 1882. It is indicated in Fig. 384. It consists in joining one of the brushes to a point half-way along the field-magnet coils, which, though connected across the mains as a shunt, must not be of very high resistance. The current in the armature can then be reversed by simply switching the second brush from one main to the other. This principle is used in Maquaire's regulator (Fig 486).

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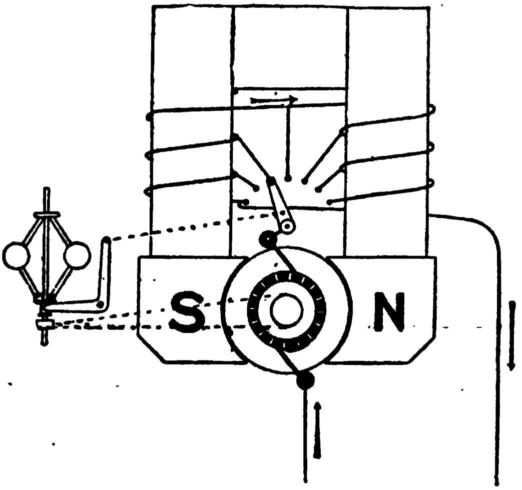
[1] Specification of Patent, No. 5122 of 1882.

GOVERNMENT OF MOTORS.

It is extremely important that electric motors should be so arranged as to run at a uniform speed, no matter what their load may be. For example, in driving lathes, and many other kinds of machinery, it is essential that the speed should be regular, and that the motor should not "race" as soon as the stress of the cutting tool is removed.

Interruptor Governor.—One of the earliest attempts to secure an automatic regulation of the speed was that of M. Marcel Deprez, who in 1878 applied an ingenious method of interrupting the current at a perfectly regular rate by introducing a vibrating brake into the circuit. The motor employed had a simple 2-part commutator, whose rotation timed itself to the makes-and-breaks of the current. This method is, however, inapplicable to large motors.

FIG. 385.



AUTOMATIC CENTRIFUGAL GOVERNOR.

CENTRIFUGAL GOVERNING.

Spasmodic Governor.—Another suggestion, equally impracticable on the large scale, was to adopt a centrifugal governor to open the circuit whenever the motor exceeded a certain speed. A motor so governed runs spasmodically fast and slow.
]

It is also possible for a centrifugal governor to be employed to vary the resistance of a part of the circuit; for example, to work an automatic adjustment to shunt part of the current of a series machine from its field-magnets, or to introduce additional resistance into the field-magnet coils of a shunt-wound machine, in proportion to the speed. A case is shown in Fig. 385, in which a centrifugal governor driven by the motor alters the number of exciting coils in the field-magnet circuit, causing the magnetism to increase if the motor runs too fast, and so brings down the speed again. This method was proposed by Brush, and answers well for motors in arc-light circuits.

Periodic Governor.—Professors Ayrton and Perry have also proposed several forms of "periodic" centrifugal governor, a device by which in every revolution power is supplied during a portion of the revolution only, the proportion of the time in every revolution during which the power is supplied being made to vary according to the speed. The main difficulty with such governors is to prevent sparking. But there is a still more radical defect in all centrifugal governors: they all work too late. They do not perform their functions until the speed has changed. The perfect governor will not wait for the speed to change.

DYNAMOMETRIC GOVERNING.

The author devised[1] another kind of governor which is not open to this objection. He proposed to employ a dynamometer on the shaft of the motor to actuate a regulating apparatus, consisting, either of a periodic regulator to shunt or interrupt the current during a portion of each revolution, or of an adjustable resistance connected in part of the circuit. The dynamometric part may take the form of a belt dynamometer (such as Alteneck's) or of a pulley dynamometer (such as Morin's or Smith's). In the latter case, which is the more convenient, a loose pulley runs on the motor shaft and is connected by a spring arrangement with a fixed pulley. The rotation of the motor will drag round the fixed pulley in advance of the loose pulley, and the angular advance will be proportional to the turning moment or torque. The amount of such angular advance determines the action of the regulating part. The regulator in this case is therefore worked, not according to the speed of the motor, but according to the load it is carrying. Any change in the load will instantly act on the dynamometric governor before the speed has time to change. If such a governor is purposely over-set it may even have the effect of causing the motor to run faster when the load comes on than it does when running idle.

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[1] Specification of Patent, No. 1639 of 1883.

ELECTRIC GOVERNING.

Another method of governing, not requiring any rotating parts, has been proposed by the author. He uses as field-magnets a double set of poles, set at different angles with respect to the brushes of the motor. One pair of magnetic poles, having a certain lead, is actuated by series coils, the other pair, having a different lead, by shunt coils. When both shunt and series are working, there will, of course, be a resultant pole having some intermediate lead. If the load of the motor is diminished it will tend to run faster. increasing the current in the shunt part, decreasing it in the series part, and therefore altering the effective lead and preventing the increase of speed.

In 1880 a motor was patented by Mr. G. G. André in which the field-magnets were wound in two separate circuits, one of thick and the other with thin wire, the current dividing between them, and the armature was connected as a bridge across these circuits exactly as the galvanometer is connected across the circuits of a Wheatstone's bridge. Motors governed on this principle have been constructed, since 1884 onwards, by Lieut. F. J. Sprague; they showed remarkably good regulation.

The method of automatic regulation that is most perfect in theory is undoubtedly that imagined by Professors Ayrton and Perry, and expounded in their paper in the *Journal of the Society of Telegraph Engineers*.[1] The theory of self-regulation propounded by them demands the most careful attention. It is expounded in the following pages; but the symbols employed have the same meaning as in the chapters which precede. Professors Ayrton and Perry originally employed an argument in which one part of the motor is regarded as acting as a brake to another part. The author prefers to regard the use of a shunt winding with an opposing series winding—which is the final result of this method of regulation—as simply a differential winding designed to produce a certain result.

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[1] Vol. xii., May, 1883; see also a later paper in *Phil. Mag.*, 1887.

THEORY OF SELF-GOVERNING MOTORS.

In the section on Self-regulating Dynamos, on pp. 277 to 294, were set forth the methods of solving the problem how to arrange a dynamo so that it shall feed the circuit with electric energy under the condition of a constant potential, when driven at a constant speed. The solution to that problem consisted in the employment of certain combinations for the field-magnets which gave an initial magnetic field independent of the current that might be flowing in the main circuit.

Now it is not hard to see that this problem may be applied conversely, and that motors may be built with a combination of arrangements for their field-magnets, such that, when supplied with currents under the standard condition of constant potential in the distributing mains, their speed shall be constant whatever the load. It will be evident without any numerical calculations that the windings must oppose one another—one must tend to demagnetize the field magnet, the other to magnetize. Take the case of a shunt motor supplied at a constant potential E, and running at a certain speed with a certain load. If the load is suddenly removed the motor will begin to race, its racing will increase the counter electromotive-force developed and will partly cut down the armature current. But the decrease of current will not be quite adequate to bring back the speed, because of the internal resistance of the armature, which has prevented the whole energy of the armature current from being utilized as work. A demagnetizing series coil of appropriate power wound on the field-magnet will, however, effect what is wanted, for then, with any reduction of load, the corresponding reduction of current can take place, the resulting increase in the field-magnetism being sufficient to get the required larger counter electromotive-force without any increase in speed. The combination may, therefore, rightly be regarded as a differential winding. For constant-current distribution no method of compound winding, whether differential or additive, has been found satisfactory; and special regulators are employed.

The following synoptical table contrasts the arrangements for self-regulating generators with those of self-governed motors:—

GENERATOR.	MOTOR.
Given Constant Speed.	*To get Constant Speed.*
To get *e constant.*	Given *E constant.*
Initial magnetism { Steel magnets. Separate excitation. Shunt coils.	Initial magnetism { Steel magnets. Separate excitation. Shunt coils.
+ Series-regulating coils.	— Series-regulating coils.

In discussing the theory of the self-governed motor, we shall follow the same general lines as in discussing the theory of the self-regulating generator, namely, find an equation expressing the desired condition of constancy.

Case (i.)—*Given: E constant.*

(*a*) *Magneto Motor with Series-regulating Coil.*—Using the same notation as previously, we have for the counter electromotive-force developed in the armature—

$$\mathrm{E} = n\,\mathrm{C}\,\mathbf{N};$$

also

$$\mathrm{E} = E - (r_a + r_s)\,i.$$

Now $\mathbf{N}$ is made up of two parts, viz.:—$\mathbf{N}_1$ the permanent part, and another part depending on the series coil which we may write $q\,S\,i$; where q has the same signification as on p. 283, and is equal to 4π divided by ten times the sum of the magnetic reluctances. Its value therefore depends upon the permeability, and therefore upon the degree of saturation of the iron of the magnetic circuit. Reserving this point for further consideration, we may write

$$\mathbf{N} = \mathbf{N}_1 - q\,S\,i.$$

If we had written + instead of –, we should find the solution coming out with the negative sign, indicating that the windings must be so arranged that the current in the series coil circulates in the negative or demagnetizing sense. We write the negative sign, however, as we already know that this must be so. We also assume at present that there are no armature reactions. Substituting the value of $\mathbf{N}$ in the fundamental equation, we have

$$E = n\,(C\,\mathbf{N}_1 - C\,q\,S\,i);$$

and equating this to the other value of E in the second equation above, we find

$$n = \frac{E - (r_a + r_m)\,i}{C\,\mathbf{N}_1 - C\,q\,S\,i}. \qquad \text{[I.]}$$

Having thus obtained an expression for the speed, we must examine the various parts of the expression to see which are variable and which constant, and so deduce a relation which shall make n constant. Now in both numerator and denominator there are two terms, the first of which is a constant, whilst the second of each contains the variable i. A little consideration will show that the fraction cannot have a constant value unless the two coefficients of the variable in the second terms bear the same ratio to one another as do the two constants which stand as the first terms; or n cannot be constant unless

$$\frac{E}{C\,\mathbf{N}_1} = \frac{r_a + r_m}{C\,q\,S},$$

or

$$\frac{E}{\mathbf{N}_1} = \frac{r_a + r_m}{q\,S}, \qquad \text{[II.]}$$

which is the desired equation of condition.

If this condition be observed (and it will be noted that the quantity of series winding required is proportional, as in the self-regulating dynamo, to the internal resistance of the machine), then the speed will be constant and of the value

$$n = \frac{E}{\mathrm{C\,N_1}} = \frac{r_a + r_m}{\mathrm{C}\,q\,\mathrm{S}}. \qquad \text{[III.]}$$

From the first of these relations we see that the speed at which the machine is thus governed to run is the same speed as that at which, if driven as a generator on open circuit, it will yield an electromotive-force equal to that of the supply at the mains. When running as an unloaded motor, it ought of course to turn so fast as to reduce the current through its armature to a minimum, which it can do by running at this speed. It is evident that by making the permanent part of the magnetism strong enough, the critical speed—that is to say, the speed for which the motor is self-governing—may be made as low as desired. As the load on the motor is increased, the flow of current through the armature must be increased, and this increased current cannot flow unless in some way the counter electromotive-force of the armature be diminished. As the speed is to be kept up, this is accomplished by the lowering of the magnetism, which occurs in consequence of the increased current flowing through the demagnetizing coils. The quantity denoted by q, which depends on the permeability of the iron, ought of course to be taken at an average value between the two extremes which it has at maximum load and at zero load. The magnetism is a maximum when the motor is running empty. When the load is greatest, if the motor is running at, say, 80 per cent. efficiency, E will be 80 per cent. of E; that is to say, $\mathbf{N}$ will be 80 per cent. of $\mathbf{N}_1$. It is between these limits in the magnetization that the value of q must be averaged. It is evident from equation [III.] that if the motor is already provided with a given series winding, there can be found a value of E, for which the condition of self-governing can be still fulfilled. All the preceding argument applies also to separately-excited motors.

(*b*) *Shunt Motor with Series-regulating Coil.*—This really includes two cases: namely, shunt and long-shunt. We take the latter case, which is the usual one. The fundamental equations will now be

$$\begin{aligned} \mathrm{E} &= n\,\mathrm{C}\,\mathbf{N}, \\ \mathrm{E} &= E - (r_a + r_m)\,i_a, \\ E &= r_s\,i_s, \\ \mathbf{N} &= q\,\mathrm{Z}\,i_s - q\,\mathrm{S}\,i_a, \end{aligned}$$

From these we get successively

$$\begin{aligned} n &= \frac{\mathrm{E}}{\mathrm{C}\,q\,\mathrm{Z}\,i_s - \mathrm{C}\,q\,\mathrm{S}\,i_a}, \\ n &= \frac{E - (r_a + r_m)\,i_a}{\mathrm{C}\,q\,\mathrm{Z}\,i_s - \mathrm{C}\,q\,\mathrm{S}\,i_a}, \\ n &= \frac{r_s\,i_s - (r_a + r_m)\,i_a}{\mathrm{C}\,q\,\mathrm{Z}\,i_s - \mathrm{C}\,q\,\mathrm{S}\,i_a}, \end{aligned}$$

which cannot be constant unless the respective coefficients of i_s and i_a in the numerator bear the same ratio to one another as do the corresponding ones in the denominator, giving as the equation of condition

$$\frac{r_s}{\mathrm{C}\,q_1\,\mathrm{Z}} = \frac{r_a + r_m}{\mathrm{C}\,q_2\,\mathrm{S}},$$

The values of q are here distinguished by suffixes for the following reason:—If the above relation is fulfilled, then when the motor runs with zero load there will be practically no current through the armature, and the counter electromotive-force $n\,\mathrm{C}\,q_1\,\mathrm{Z}\,i_s$ will be equal to E. At this stage of things, when the shunt coil is in full work, the magnetism is at its maximum, and q_1 (which is proportional inversely to the total magnetic resistance) will be at its minimum value. On the other hand, when the motor is driving its maximum load, the armature current (and therefore the demagnetizing effect of the regulating coils) is at its maximum, the magnetization will be at its lowest running value, and q_2 will be at its maximum. This being premised, the equation of condition may be written

$$\frac{Z}{S} = \frac{r_s}{r_a + r_m} \cdot \frac{q_2}{q_1} \qquad \text{[IV. (a).]}$$

In the earlier editions of this work saturation was left out of account, and the formulæ were only approximate, the equation having the form

$$\frac{Z}{S} = \frac{r_s}{r_a + r_m}, \qquad \text{[IV.]}$$

which is Ayrton and Perry's rule for the winding of the self-governing motor. It may be remarked, however, since in a well-designed motor the resistances in the armature-circuit are very small, and the efficiency as a whole high, the demagnetizing effect of the series coils, even at full load, need only reduce the magnetization by a small percentage, so that q_2 may be nearly equal to q_1. Moreover, if a backward lead be given to the brushes, the armature itself may act partially as a demagnetizing series coil, and so compensate for alteration in the permeability. It is quite certain that motors wound differentially in the proportion indicated in equation [IV.] are very nearly self-governed. Some excellent motors by Lieut. F. J. Sprague are wound according to this rule. One very curious property of this method of winding is as follows:—Suppose the motor to be standing still and the current turned on, the ampere-turns due to the shunt will be equal to $E\ Z \div r_s$, whilst those due to the series coil will be $E\ S \div r_a + r_m$; and these, according to equation [IV.], will be equal, and they are of opposite sign. There should then be no magnetism excited at all. But if there is any lead at the brushes, the magnetizing tendency of the armature will come into play; and if the brushes have a considerable negative lead, the effect will be to magnetize the field-magnet in the wrong sense, and then the motor starts the wrong way. The defect might be remedied by cutting out the series coil or reversing it, until the motor has got up its speed. The latter course is preferable, as the additional torque of the series motor is of great advantage in overcoming the statical resistance to motion experienced at starting.

It is obvious that the number of shunt-turns should theoretically be such that the motor, driven on open circuit at the given speed, shall generate an electromotive-force equal to E.

Practical Determination of the Shunt and Series Windings.[1] —As in the case of compound winding of dynamos (p. 292) so for motors, the proper windings can be found by simple experiments, a temporary coil being wound and separately excited, and a resistance equal to the future r_m being added to the armature resistance. Two experiments are required. Run the motor first with no load at the brake, using the proper potential E, and excite the temporary coil, observing the number of ampere-turns that are needful to bring the speed down to the required n. The number of ampere-turns in this case is equal to $Z\ i_s$, where i_s is the current, which economy dictates should be used in the shunt. Secondly, run the motor with its fullest load at the brake, and again excite the field-magnet with such a number of ampere-turns that the speed is constant at n. From this and the previous experiment S can be calculated.

The efficiency of a differentially-wound motor cannot be expected to be as high as that of one which is non-differentially wound, since the energy expended in the former case in magnetizing the field-magnets is greater relatively to the amount of magnetization produced. Thus, if the demagnetizing coil has a value in ampere-turns of one-fourth of the magnetizing coils, the energy required to give the necessary magnetization will be 50 per cent., or half as much again as in the case of simple direct magnetization.[2]

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[1] It should be pointed out that this process differs from that suggested by Professors Ayrton and Perry in their paper on electromotors, in *Journal Soc. Teleg. Engineers*, May. 1883. Their method depends on the volume left on the bobbins of the field-magnets, which is assumed to be constant.

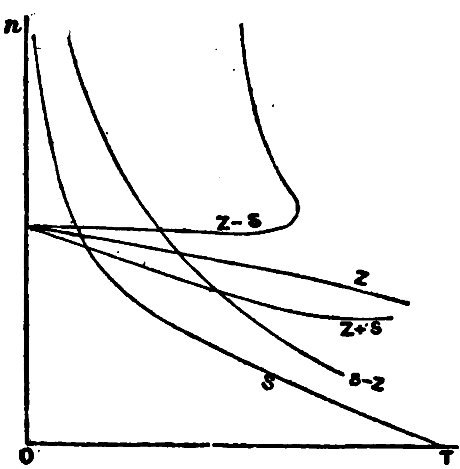
[2] Some elaborate observations upon compound-wound motors, when worked with constant potentials and constant currents, have been published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for June. 1885.

MECHANICAL CHARACTERISTICS OF COMPOUND DIFFERENTIAL MOTORS.

It may be convenient here to consider the graphic representation of the regulations between speed and torque in motors provided with mixed windings.[1]

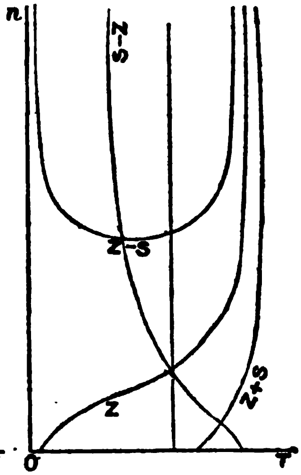
The curves for constant-potential supply are shown in Fig. 386, wherein the letters S and Z refer to series windings and shunt windings respectively. The forms of the curves for mixed windings differ somewhat according to the proportions of the two sets of coils. The important case is that of the differential winding marked Z – S, having a few series turns to correct the droop of the pure shunt-winding, and it will be noted that up to a certain limit the speed is nearly constant, but that there is a maximum value to the torque. In the

FIG. 386.



MECHANICAL CHARACTERISTICS AT CONSTANT POTENTIAL.

FIG. 387.



MECHANICAL CHARACTERISTICS WITH CONSTANT CURRENT.

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[1] The author is indebted to Frölich's *Die Dynamoelektrische Maschine* for the curves of motors with mixed windings. Similar curves have been deduced by Rechniewski, see *Séances de la Société de Physique*, 1885, p. 197.

case of constant-current supply, as the curves of Fig. 387 show, the only winding which gives any approximation to a constant speed is the differential winding with large shunt and small series coil. For, as in the case of the constant-current generator, the variation of the magnetism has to be carried through an enormous range, defying any averaging of the magnetic permeability.

An elegant graphic method of treating the problem of self-government of motors is given by M. Picou in *La Lumière Electrique*, xxiii. 114, 1887.

OTHER METHODS OF GOVERNING MOTORS.

A further suggestion for governing motors is due to Mr. Mordey and Mr. C. Watson. They wind the armature with two windings, having separate commutators. One winding—the main one—is the ordinary armature circuit of the motor, and is supplied with current from the external source, causing the armature to revolve. The other winding, which may be called the regulating armature-winding, is small in amount, and is disposed over, or side by side with, the main motor-winding. This additional winding is not connected to the mains or source of current, but to the field-winding by means of a special commutator or collector and brushes. It will be observed that this additional armature-winding, revolving in the field, constitutes a generator of current. The regulating action is as follows:—When a tendency to increase in speed results from a diminution of the load, the additional armature-winding tends to increase the strength of the field by supplying more current to the field-coils, and thus raises the opposing electromotive-force of the motor, diminishes the amount of current received from the mains, and so reduces the speed to its normal rate. Again, an increase of the load, tending to reduce the speed, is counteracted by a lessening of the magnetizing current produced by the additional winding, a consequent lowering of the opposing electromotive-force of the motor, and an increase of the current received from the mains. It will be seen that as this plan is summative it does not require so great an expenditure of energy in the fields as a differential winding; nor is it open to the objection that the motor may start in the wrong direction. On the other hand, it has the drawback of requiring an additional commutator. The method has given very good results, but has been rendered unnecessary, except in special cases, by the simpler plan to be next described. This is the important discovery by Mr. Mordey,[1] that if a pure shunt motor is constructed upon perfect designs—that is to say, having very small resistance of armature and very large resistance of shunt, and having also field-magnets, which are very powerful relatively to the armature, and an armature properly laminated and sectioned so as to reduce eddy-currents and self-induction to a minimum—such a shunt dynamo, if supplied from mains at a constant potential, will run at a constant speed whatever the load.[2] The slight demagnetizing action of the armature when a negative non-sparking lead is given to the brushes acts, in fact, instead of any special demagnetizing coil. The following tests showed a constancy to within 1½ per cent., for all loads within working limits.

Potentials at Terminals.	Current (amperes).	Horse-power at Brake.	Revolutions per Minute.	Torque (pound-feet).
68·4	44	1·1	1125	5·15
68·4	126	7·4	1120	33·4
68·4	165·5	10·36	1115	48·8
68·4	180	11·14	1110	53·0

With a lower electromotive-force the same motor regulated almost equally well, but at a lower speed. It was observed that, especially when the motor was giving out small horse-power, that the speed was increased by weakening the field.

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[1] See *Phil. Mag.*, January. 1886.

[2] This might have been foreseen from the equations of p. 602, in which if $r_a + r_m = 0$, the condition of regulation will give $S = 0$.

A possible mode of governing constant-current motors is by providing a variable magnetic shunt, in the converse of the manner suggested by Trotter for constant-current generators. Various other modes[1] of controlling the speed by altering the magnetism have been suggested, but few of them are automatic or reliable.

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[1] See a most interesting and fully illustrated paper by Mr. F. B. Crocker in *Electrical World*, xiii. 311, 1889.

CHAPTER XXI.

MODERN FORMS OF CONTINUOUS CURRENT MOTORS.

ALMOST any good modern dynamo (independently excited, shunt wound, or compound wound) will serve as a motor on mains supplied at the proper pressure; but attention has to be paid to the setting of the brushes that it may run rightly, and the machine so used must be one that will give the proper voltage at the proper speed. In designing motors precisely the same principles hold good [1] as obtain for designing generators; for the same features, namely, low internal resistance, powerful field-magnets, and proper elimination of eddy-currents, which go to make a good generator, also apply to the making of a good motor. For example: suppose it is desired to design a 10 HP. motor to run at 500 revolutions per minute, when fed at 200 volt mains. Now 10 HP. is 7460 watts; a motor to give out actually 7460 must be allowed to absorb (at 85 per cent. nett efficiency) 8776 watts. Further, if its electrical efficiency is to be, say, 90 per cent., it must generate 180 volts of counter electromotive-force. Dividing 8776 watts by 180 volts we find 48·75 amperes as the current it must take at normal load. If, therefore, we simply set to work to design a dynamo with good powerful field-magnets capable of generating 50 amperes at 180 volts at a speed of 500 revolutions per minute, we shall have obtained what we wanted.

Snell has given the following rules for expressing the actual HP. which may be safely and continuously taken from motors:—

Ring armatures, 2-pole; HP. $= 0{\cdot}00001 \times ld^2 n$,
Drum armature, 2-pole; HP. $= 0{\cdot}000015 \times ld^2 n$;

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[1] For discussion of the subject of motor design, see a paper by Snell in *The Electrician*, xxii. 313 and 403, 1889; also *Journ. Inst. Electr. Engineers*, xx. 1891.

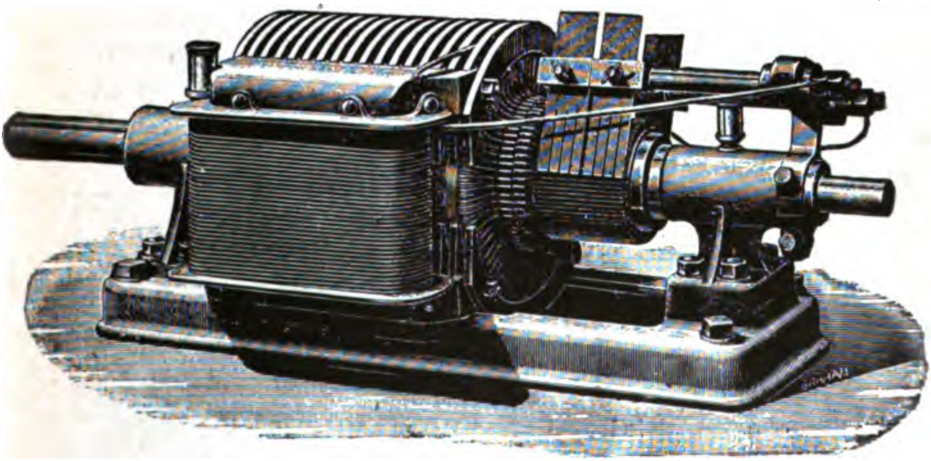
where l is length of armature and d its diameter, in inches, and n the revolutions per minute.

It might be supposed from the opening statement that any description of motors was superfluous. There are, however, certain special forms of machine that have come into notice as motors, and are, therefore, described here.

Ayrton and Perry's Motors.—Amongst the motors which were at one time in commerce were special forms by Ayrton and Perry, with a fixed external ring armature and an internal revolving field-magnet. These motors were illustrated in the earlier editions of this book. They had the structural defect of possessing too weak a field-magnet to enable them to run sparklessly, and though remarkably compact and convenient, fell into disuse.

Reckenzaun's Motors.—Mr. A. Reckenzaun has developed a design of motor, with special reference to the requirements of electric tramcars and launches. Cast-iron, on account of the greater weight and dimensions, is here avoided, and the field-magnets are built up of thick wrought-iron plates, bent hot into such a shape as to form double horseshoe magnets with the ends turned inwards. These ends are

FIG. 388.

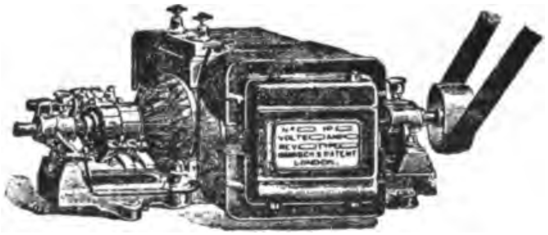


RECKENZAUN'S MOTOR.

notched out to receive a series of segmental iron pieces which form the poles, as will be seen by the illustration (Fig. 388). This machine is light for its power, compact and strong. The entire height, for example, of a tramcar motor giving 8 HP. at 800 revolutions is only 13 inches; it weighs complete 600 lbs., and is capable of working up to 12 HP. (brake) for short periods. The armature, Gramme type, is 11 inches long. The section of the armature iron core is 10½ inches by 1⅞ inches, and that of the field-magnet cores 9 inches by 1⅞ inches. The magnets are series-wound, each limb containing two coils (in some cases three), which can be put in parallel or series so as to vary the exciting power and permit of obtaining the different rates of speed and power required in tramway work, without resorting to artificial resistances, and also of obtaining a great torque in starting, when all the coils are in series.

Immisch's Motors.—Mr. Moritz Immisch for many years constructed motors well known for their excellent mechanical construction, high efficiency, and great power in proportion to weight. Only those of smallest size have ring armatures, all others have drum armatures, and the field-magnets are usually of the double-horseshoe type, as shown in Fig. 389. A section of the machine, one-fifth of the full size, is shown in Fig. 390. The armature is 15 m. in diameter, and 1400 revolutions per minute gives 8 HP. on the shaft, with an efficiency of 85 per cent. It weighs only 350 lbs.

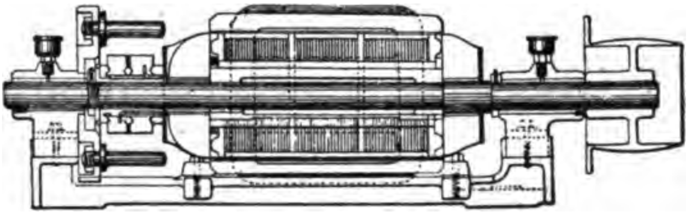
FIG. 389.



IMMISCH'S MOTOR.

The armature core consists of thin iron disks insulated with thin asbestos, having at the ends, and at intervals, thicker disks provided with projected driving-teeth, all the disks being securely keyed to the shaft. The windings are carefully insulated with Willesden paper protected with india-rubber varnish. The arrangement of the armature presents certain peculiarities, amongst which are the commutator connexions. The bars of the commutator or collector are grouped alternately in two sets, side by side, so that a single broad brush, or two brushes side by side in one holder, will always cut out of circuit the coil of the armature that is connected from the bar of the front set to the bar of the back set; the effect being exactly the same as if an ordinary collector were used with two pairs of connected brushes, those of each pair being set apart to a distance equal to the breadth of a single bar. The effect of cutting out the coils as they reach the neutral point is, according to the inventor, to diminish cross-magnetizing influences and obviate changes of lead; the brushes being set, once for all, in the required position. Some brake tests made in the presence of the author on a small ½-HP. motor, weighing about 20 kilogrammes (of which only about 8·5 kilogrammes were of copper), gave following results:—

Fig. 390.



Immisch's Motor (Section).

Revolutions per Minute.	Volts.	Amperes	E. HP. absorbed.	HP. given out.	Efficiency.
1420	40	10·5	·565	·354	·625
1840	49	10·5	·69	·46	·666
1920	50	11	·74	·48	·645
2280	61	12	·97	·57	·587

A large 30-HP. motor, weighing 850 kilogrammes, gave following results:—

Revolutions per Minute.	Volts.	Amperes.	E. HP. absorbed.	HP. given out.	Efficiency.
660	500	49	33	29·8	·90
680	500	48	32·2	29·5	·91
675	500	49	33	29·5	·89

The Immisch motors are now made by the General Electric Traction Co., whose engineer, Mr. A. T. Snell, has designed many large motors for traction and mining[1] purposes. In many of these motors carbon brushes, Fig. 277, p. 382, are now used. The mode of driving the core-disks of the large machines is shown in Fig. 251, p. 352.

The "Agir" Motor.—This motor, designed by Messrs. Andersen and Girdlestone (the "Industries" prize motor), is shown in Fig. 391, and its details of construction are given in full in Plates XVIII. and XIX. It was designed to meet the requirements of running at 250 revolutions per minute on 150 volt mains. It weighs 943 lbs., and when tested gave following results:—

Electrical HP. supplied	11·81	12·70	14·84
Speed of motor spindle	248	252	285
Mechanical HP. output	7·31	9·48	10·6
Nett efficiency	61·9	74·7	71·4

Brown's Motors.—Of these some mention is made in Chapter XXVI., and a large 4-pole motor of 240 HP. is described on p. 491.

Laurence, Paris and Scott's Motors.—Many firms now regularly supply motors of all sizes: this firm has kindly supplied the following particulars of a shunt-wound motor taking 10 amperes from 100 volt mains, and giving out a little over one actual HP.

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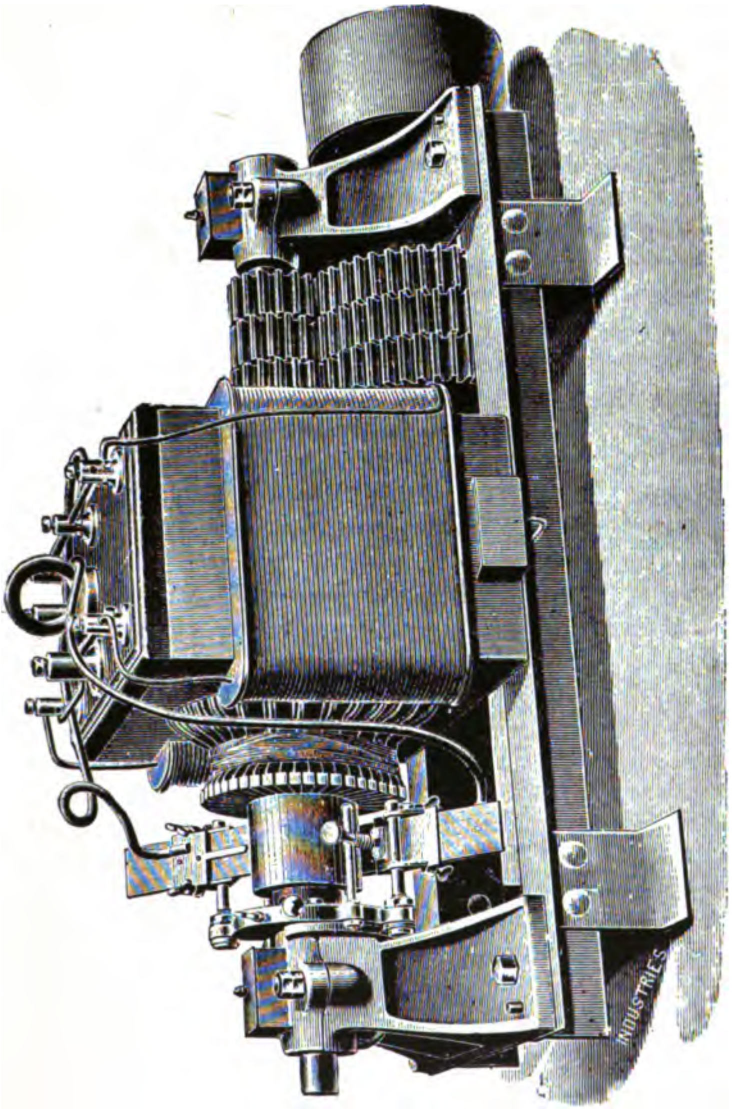
[1] See notes by Mr. Snell on Electrical Work in Mines, in *Proc. South Wales Institute of Engineers*, July 27, 1891. Also lecture on *Electricity in Mining* by author of this book, published by Messrs. Spon.

Armature 2-pole, drum-wound; diameter of armature core, 4½ inches, length of core, 4 inches; sectional area of iron in core, 7·6 square inches; number of segments of commutator, 36; turns per section, 10, No. 19, or 42 mm. wire; total number of turns, 360;

FIG. 391

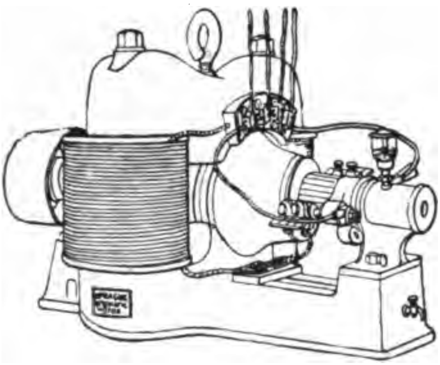


THE "AGIR" MOTOR (ANDERSEN AND GIRDLESTONE'S).

weight of wire on armature, 3½ lbs.; resistance of armature, 1·06 ohm (hot); magnet cast iron, 17·72 square inch area; shunt winding, 15 lbs. 9 oz., No. 23, or 25 mil wire, resistance 140 (warm); turns in shunt winding, 4960; starting coil on one limb only, 560 turns, No. 20, or 35 mil wire, 3 lbs.

Sprague's Motors.—Lieut. F. J. Sprague, of New York, has produced several forms of motor of excellent design and construction, many hundreds of them being in use in the States. One form of these machines is shown in Fig. 392. For further details the reader is referred to the accounts published in the technical press.[1] Sprague's method of winding the field-magnets with a differential compound winding is identical with that invented in 1883 by Ayrton and Perry, depending upon the use of a coil in series with the armature to demagnetize and weaken the field.[2] Many other ingenious methods of governing and practical applications have been worked out by Sprague.

FIG. 392.



SPRAGUE'S MOTOR.

Goolden's Mining Motor.—Mr. Atkinson has designed for Messrs. Goolden and Co. a mining motor of the same type as

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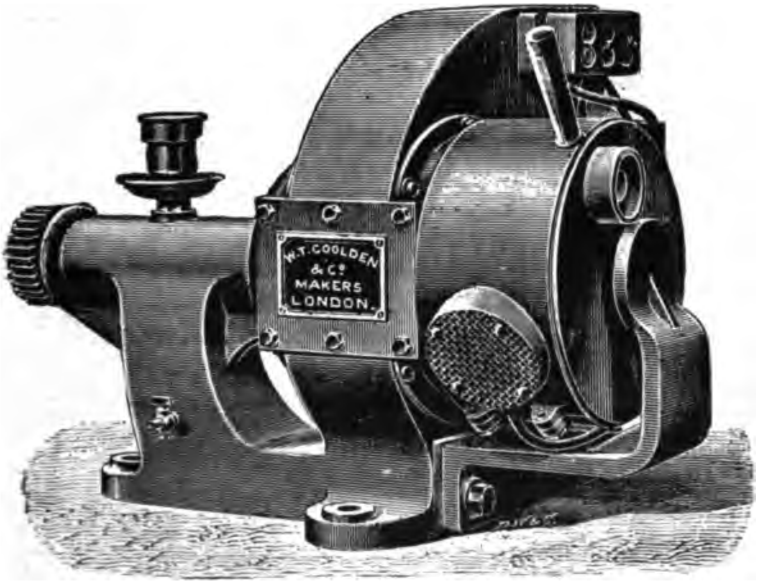
[1] *Electrical World*, October, 1886; also Martin and Wetzler's treatise on *The Electric Motor*, 157-75; and *Electrical World*, xiv. 3, 1889; xv. 370 1890; also *The Electrician*, xxiv. 248, 1890.

[2] See Specifications of British Patents, Nos. 15,768 of 1884, and 3524 of 1885.

Fig. 121, p. 200, but with special adaptations for use in coal-mines;[1] the moving parts being enclosed so that all possibility is removed of a spark at the brushes causing an explosion. As shown in Fig. 393, the commutator and brushes, which are of carbon, are completely boxed in.

Fig. 393.


W.T. GOOLDEN & Co MAKERS LONDON.
333

Goolden Enclosed Mining Motor.

Electric Locomotive Motors.—Many motors have been designed for propelling tramcars and for electric railways; the points that inventors have chiefly considered being strong mechanical design of armature, slow speed with or without gearing, and construction that will resist deterioration by water, mud, dust, or overheating. Owing to the enormous rush of current just at starting, the armature must be capable of enduring the severest torque, and be practically fire-proof as well as water-proof. All gearings for speeding down have gradually fallen into disfavour, direct-driving slow-speed forms[1] being more reliable. All this implies the employment of motors with relatively powerful field-magnets. This is not the place to enter on a detailed account of electric locomotion in general or to describe any of the hundreds of electric tramways and railways now running. In Plate XX. is given a sketch of the electric locomotive of the City and South London subway-railway, with two 50 HP. motors designed by Hopkinson and constructed by Messrs. Mather and Platt. Fourteen of these locomotives are now running, and also two others by Siemens of a pattern in which the field-magnets are relatively more powerful, enabling the armature to give the requisite torque with less current. A smaller example is afforded by the 20 HP. motor used in the Bessbrook Tramway, described by E. Hopkinson,[2] which ran at 100 revolutions per minute, taking 100 amperes at 220 volts. It was series-wound, the resistance of armature being 0·112 ohm, and of magnet 0·113 ohm. The nett efficiency was over 90 per cent. The field-magnet being very powerful, this motor is reversed by simply reversing current in the armature.

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[1] See the author's *Electricity in Mining*, p. 38, for descriptions of electric coal-cutters and other mining appliances.

Constant Current Motors for Arc Light Circuits.—For insertion in a series circuit special forms of motor are needed, most of them having governors of centrifugal type, to regulate the power taken from the mains; most of these are of American origin.[3]

Small-power Motors.—Several makers have given special attention to small-power motors for driving fans and other light running machinery. In England, Messrs. Cuttriss, of Leeds; in France, M. Trouvé; in Germany, various makers, in particular the Allgemeine Co., of Berlin; in the United States, Messrs. Curtis, Crocker, and Wheeler,[4] have all done good work.

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[1] As a recent example, see the Thomson-Houston slow-speed motor described in *Electrical World*, xvii. 93, 1891.

[2] *Proc. Inst. Civil Engineers*, xci. part i., 1887–8.

[3] See *Electrical World*, xv. 269, 1890; xvii. 120 and 130, 1891; also *The Electrician*, xxv. 16, 45, and 131, 1890.

[4] See *Engineering*, xliv. 83, 1887; also *Electrical World*, ix. 4, 9, and 203; xiii. 309, 1889; xv. 114 and 269, 1890; xvii. 130, 191.

Pulsating Motors.—The early type adopted by Page, Hjorth and others, in which a purely reciprocating movement instead of a rotatory one was produced, has been revived in recent years for motors for the special purposes of operating hammers or drills. In 1879, Werner von Siemens[1] produced a mining drill in which a direct current and an alternating current of slow period were combined to produce a reciprocating movement without any commutator—a device lately revived by Atkinson and by Van de Poele. In 1880 Marcel Deprez[2] designed an electric hammer for forging, having a plunger of iron to be drawn up and down in a cylindrical coil wound in sections into which the current was successively led by a commutator.

Alternate Current Motors.—These are specially treated in Chapter XXIV.

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[1] D. R. Patent, No. 9469 of 1879 (see vol. ii. p. 389, of Siemens' *Arbeiten*).

[2] *La Lumière Electrique*, ix. 44, 1883.

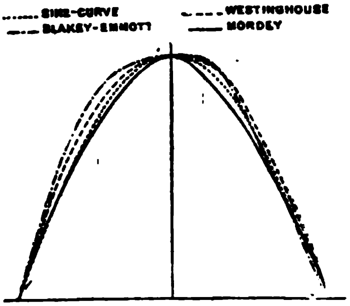
CHAPTER XXII.

THE PRINCIPLES OF ALTERNATE CURRENTS.

IN alternate-current working the current is rapidly reversed, rising and falling in a succession of impulses or waves. Electricity is in fact oscillating backwards and forwards through the line with enormous rapidity, under the influence of a rapidly-reversing electromotive-force. The adjectives *alternate*, *oscillatory*, *periodic*, *undulatory*, and *harmonic* have all been used to describe such currents. The author would prefer the term *wave-currents* as being both shorter and more apposite. The properties of alternate-currents differ somewhat from those of direct or continuous currents. They are affected not only by the resistance of the circuit but also by its inertia or self-induction, which diminishes the amplitude of the waves, retards their phase, and smooths them down in general. On account of these peculiarities, some preliminary account of them is needed.

We have seen (p. 30) how the repeated approach and recession of a coil and a magnet pole will set up alternate electromotive-forces; and how (p. 213) the rotation of a simple loop in a uniform magnetic field will give rise to a truly periodic wave-current. We have seen also how the value of the periodic electromotive-force at any moment may be expressed in terms of the sine of the angle through which the coil has been turned. In the case of real machines in which the magnetic fields are not uniform, nor the coils simple loops, the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape of the polar faces, and on the form and breadth of the coils. Consider the case of a machine in which the field-magnets consist of a double crown of opposing poles (as in the machines of Wilde, Siemens, Ferranti, Mordey, &c.). If the armature coils and magnet cores are both of circular form, and equal in diameter, as the coils approach the polar ends of the cores they will, it is true, gradually enter the field, and the number of lines cut by the coil during equal displacements will gradually increase and become a maximum when the axis of coil and core coincide, and from that point it will again decrease, almost in a sine law; the greatest rate of cutting being when the edge of the coil is opposite the centre of the core; but if coil and core be rectangular in outline, the greatest rate of cutting in each wire will be when one edge of the coil is passing the edge of the pole. In this case the sine law cannot be true for the electromotive-force. In order to test whether in any given dynamo the rise and fall of electromotive-force and of current in the armature coils conforms to the law of sines, experiments are necessary. Joubert, in order to measure the currents of a Siemens' dynamo, employed an electrometer method, and took off the current at any desired phase by a special commutator, and found an approximate curve of sines.[1] Another method, applicable also to direct-current machines, due to Mr. Mordey, is described.

Fig. 394.



Curves of Alternators.

In Fig. 394 are given four curves for a half-period. Of these one is a sine curve, the other three form actual alternators, showing how nearly they agree with a true sine curve. The one which agrees most nearly is that of the Mordey alternator, which lies just within the sine curve nearly throughout its whole extent. We are then sufficiently justified in assuming that the impressed electromotive-force follows a sine law, so that the electromotive-force at any instant may be expressed in the form—

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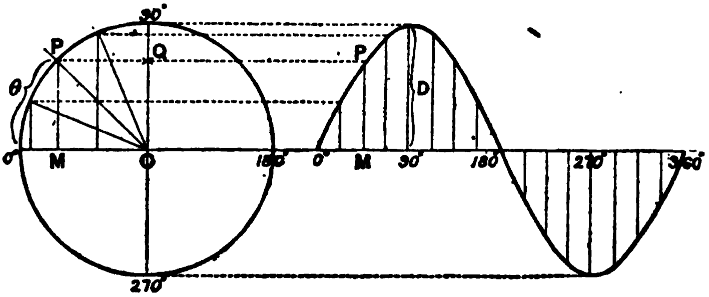
[1] For modern varieties of this method see p. 73, on which references are given. For the most recent research see paper by Dr. J. Linde in *Elektrotechnisches Echo*, No. 20, 1891.

$$E_\theta = D \sin \theta,$$

where D is the maximum value or *amplitude* attained by E, and θ an angle of *phase* upon an imaginary circle of reference. Consider a point P revolving clock-wise round a circle. If the radius of this circle be taken as unity, P M will be the sine of the angle θ, as measured from 0°. Let the circle be divided out into any number of equal angles, and let the sines be drawn similarly for each. Then let these sines be plotted out at equal distances apart along the horizontal line, as in Fig. 395, giving us the sine curve.

In Fig. 395 one revolution of P around the circle of reference corresponded to one complete alternation or cycle of changes. The value of the electromotive-force (which varies between + D and − D as its maximum values) may be represented at any moment either by the sine P M or by projecting P on to the vertical diameter, giving O Q. As P revolves, the point Q will oscillate along the diameter.

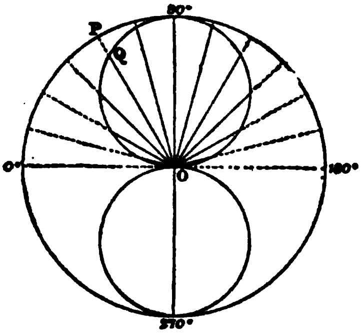
FIG. 395.



CURVE OF SINES.

There is yet another way of representing periodic variations of this kind, namely, by a diagram akin to that used by Zeuner for valve-gears. Let the outer circle (Fig. 396) be as before a circle of reference around which P revolves. Upon each of the vertical radii describe a circle. Then the lengths such as O Q cut off from the radii, represent the corresponding values of the sine of the angle. If a card with a narrow slit cut radially in it were made to revolve over this figure, the intersection with the two inner circles would show the varying electromotive-forces in various positions.

FIG. 396.



The reader who desires to pursue the graphic study of these matters further should consult the excellent treatise of Prof. Fleming,[1] or that of Mr. Blakesley,[2] and sundry papers by Mr. Kapp.[3]

We must now show how to calculate the rise and fall of current which the periodic electromotive-force sets up in the circuit. Those who are afraid of calculations should go on to the geometrical treatment of the problem, p. 627.

Analytical treatment.—To calculate this rise and fall we must remember that the motions of the rotating coils are supposed to take place with a uniform speed, and that the induced electromotive-force will be proportional to the rate of change in the number of magnetic lines induced through the circuit. To get a complete account of the action we must take into consideration the number of magnetic lines *induced by the circuit on itself.*[4]

Consider a simple loop of wire traversed by a current. Every portion of the loop will be surrounded by a whirl of magnetic lines similar to those of Fig. 13, and those belonging to the current in one half of the loop tend to influence the current in the other half. Such influence or tendency of the current's lines to influence the other parts of the circuit is, however, only manifested when the strength of the current or the shape of the circuit is changing. We know that any increase in the number of magnetic lines that thread through a circuit (as, for example, by poking a magnet pole into it) tends to set up a current that will oppose the motion. Any increase in the strength of the current in the loop will increase the number of lines through the loop, and that increase will of itself tend to set up an opposing current. On the other hand, any decrease in the current in a circuit, by reducing the number of magnetic lines which thread through the circuit, tends to oppose the reduction of the current. A current, in fact, acts as if it had inertia, and tends to keep the number of its magnetic lines constant. This inertia of the current in a circuit is also known as the induction of the circuit on itself, or, briefly its self-induction. The self-induction in a circuit, which, as we have seen, is due to the number of magnetic lines threaded through the circuit itself by the current flowing in it, is always made up of two factors. When discussing the earlier case of the induction of a current in a loop by rotating it in a uniform magnetic field we neglected self-induction and considered the number of lines of force which were cut by the loop as being the product of two factors, viz. the total number of magnetic lines N that actually traverse

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[1] Fleming, *The Alternate Current Transformer*, London, 1889.

[2] Blakesley, *Alternating Currents of Electricity*, London, 1889.

[3] Kapp on 'Alternate Current Machinery.' *Proc. Inst. Civil Engineers*, 1889, pt. iii.

[4] Neumann's mathematical investigation of the effect of considering the

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self-induction of the circuit in relation to a periodic electromotive-force, was published in 1845, but self-inductive phenomena had previously been studied by Henry and by Faraday.

Other mathematical investigations of alternating electric currents have been given by Weber in his *Elektrodynamische Maasbestimmungen*, and by the following :—

Koosen, *Pogg. Ann.*, lxxxvii. 386, 1852.

Le Roux, *Ann. Chim. Phys.* [3], l. 463, 1857.

Clerk Maxwell, *Phil. Trans.*, 1865, p. 473.

Jamin and Richard, *Ann. Chim. Phys.* [4], xvii., 276, 1869.

Joubert, *Ann. de l'Ecole Normale Supérieure*, x., 1881 ; and *Journal de Physique*, s. ii., t. ii., p. 293, 1883.

Lord Rayleigh, *Phil Mag.*, May 1886, p. 375.

Hopkinson, Lecture at Instit. Civil Engineers (on Electric Lighting), 1883.

" *Journal Soc. Telegr. Engineers*, xiii.

" *Proc. Roy. Soc.*, Feb. 1887.

Abstracts of the most important of these will be found in Fleming's book on the *Alternate Current Transformer*.

the iron core of the armature, and C, the number of conductors at its periphery. In the case of self-induction the two factors will be different. The number of lines of force induced on itself by the current in a loop will be proportional to the strength of the current *i*. The number will, for a simple circular loop, be also proportional to the area of the loop. But for loops that are not circular, and for loops that consist of many turns, and for loops that have iron in them, a much more complicated investigation would be required than could be undertaken here if it were not for one fortunate circumstance. Suffice it to say that for a loop of many turns the coefficient of self-induction is proportional to the *square* of the number of turns. For each turn helps to produce magnetic lines and also adds to the "cutting" of the lines by the circuit. As a matter of fact, the two factors of self-induction are current *i*, and a quantity symbolized by the letter L, called "*the coefficient of self-induction*," which represents the number of magnetic lines which the circuit would enclose or induce on itself if the current flowing in it were one "absolute unit." It follows at once that if current *i* flow through a circuit whose coefficient of self-induction is L, the whole self-induction of the circuit will be equal to L times *i*; and the product L *i* will represent the total amount of enclosing of magnetic lines by the convolutions of the circuit. It will also be evident that if a current begins from strength 0 and grows uniformly until its strength is *i*, the *average* self-induction in the circuit will be $\frac{1}{2}$ L *i*.

Returning now to the case of a loop having S_2 turns, placed at such an angle θ (measured from the initial position as in Fig. 134, where it stands right across the field), we see that it no longer encloses the whole number of magnetic lines which are present in the magnetic circuit. When we omit all account of self-induction, we may write

$$N_1 = S_2 N \cos \theta, \qquad [I.]$$

where N_1 is the virtual amount of enclosing of lines by the circuit.

But we know that if there is a current i in the circuit, we ought to write the equation in full—

$$N_1 = S_2 N \cos\theta + L\,i. \qquad [II.]$$

Our omission of the self-induction term in all the previous equations was only justifiable on the assumptions—firstly, that the field-magnets so overpowered the armature as to make the second term negligible; secondly, that the equations we obtained were the equations for *steady* currents.

Now we know that any variation in N_1 will set up induced electromotive-force, and that at any moment the electromotive-force will have the value

$$E = -\frac{dN_1}{dt}; \qquad [III.]$$

where we use the negative sign to show that an increase in N_1 will produce an inverse or negative electromotive-force. We are obliged to take note henceforth of the signs of the various quantities. Any change in N_1, from whatever source arising, will set up electromotive-force. We cannot well alter S_2, the number of coils of our armature. N can be altered; and in most modern alternate-current machines it is arranged that N, the number of magnetic lines in the field, can be controlled by hand or otherwise, the field-magnets of the alternate-current machine being usually separately excited by a constant current from a smaller dynamo, called the "exciter" (see Figs. 426 and 436). While the dynamo is at work, the coefficient of self-induction of the armature cannot be changed at will, as that depends on the size, shape, coiling, and coring of the armature, and on magnetic permeability; but it is possible to change the self-induction of the rest of the circuit. If we suppose this to remain constant then the only quantities that are really important in respect of the variations they will undergo—the only quantities whose variations contribute to the variations of N_1—are θ and i. The angle of position θ varies from 0 to 2π (radians); that is to say, from 0° right round to 360°, and then recurs; and its cosine therefore fluctuates between 1 and -1. The current i varies also from a certain maximum value $+i_{max.}$ to an equal negative value $-i_{max.}$. We will neglect all the variations of the other quantities, not because these variations would not be instructive—for that would be quite untrue—but because of their lesser practical importance. Then we have

$$E = -\frac{dN_1}{dt} = -\frac{d(S_2N\cos\theta + Li)}{dt}.$$

Now suppose that while the armature loop has turned through the angle θ, the time occupied—a small fraction of a second—is t. Also take T to represent the time taken for one revolution; so that if there were n revolutions[1] per second, T will be $\frac{1}{n}$ of a second. Then obviously θ will be the $\frac{t}{T}$ part of a whole revolution, and as there are 2π radians in a circle, the angle expressed in radians will be

$$\theta = 2\pi\frac{t}{T} = 2\pi n t = \omega t;$$

where ω is the angular velocity.

Inserting this value, and performing the differentiation, we get

$$E = 2\pi n S_2N \,.\, \sin 2\pi n t - L\frac{di}{dt};$$

$$E = \omega S_2N \sin\omega t - L\frac{di}{dt}. \qquad [IV.]$$

Consider this equation carefully. It shows us that if there were an open circuit, so that there could be no i, then self-induction would not come in at all. Also if the motion were so slow that the rate of change of i were inappreciable, then the second term might be neglected. The negative sign also indicates that that part of the electromotive-force which is due to self-induction opposes the other part. Suppose we pause for a moment to consider the case of slow motion, and neglect the self-induction term; then we get

---

[1] For multipolar machines the number of alternations is more numerous than the number of revolutions in proportion to the number of pairs of poles. The symbol n will in this case stand for alternations.

$$E = 2\pi n S_2 N \sin\theta,$$

which is twice the value found on p. 231 for a direct-current machine in which the windings were not all in series, but grouped in two sets in parallel. Further, since the average value[1] of the sine between 0° and 90° is $\frac{2}{\pi}$, we get, as the average value of E,

$$E \text{ (average)} = 4 n S_2 N.$$

Also it is important to notice, that with slow rotation, if the resistance of the circuit be R, the current will be at any moment

$$i = \frac{2\pi n S_2 N}{R} \sin\theta. \qquad \text{[V.]}$$

Now write D for the group of symbols $2\pi n S_2 N$, and we get—

$$i = \frac{D \sin\theta}{R}. \qquad \text{[VI.]}$$

We now pass on to entertain the case where the rotation is so quick that we must take in the self-induction term. Remember that though self-induction will set up perturbing electromotive-forces and diminish the impressed electromotive-force, yet if the nett effective electromotive-force at any instant is known the corresponding instantaneous value of the current can be calculated from it by simply applying Ohm's law. So if E, as found in formula [IV.], p. 626, be the effective electromotive-force, we may write $E = Ri$; whence

$$Ri = D \sin\theta - L\frac{di}{dt}.$$

[illegible] $= \cos^2 x - \sin^2 x$

$= 1 - 2\sin^2 x$

$\therefore \sin^2 x = \frac{1 - \cos 2x}{2}$

---

[1] Or more strictly

$$\frac{1}{\theta}\int_0^\theta \sin\theta \, d\theta = \frac{1 - \cos\theta}{\theta},$$

whence, if $\theta = \frac{\pi}{2}$, the average is $\frac{2}{\pi}$.

This is a differential equation of the form

$$a\,y + b\frac{dy}{dx} = \sin c\,x.$$

(See Boole's *Differential Equations*, p. 38.)
The solution is

$$i_\theta = \frac{D \cos \phi . \sin (\theta - \phi)}{R} + C\,\epsilon^{-\frac{R}{L}t}; \qquad [\text{VII.}]$$

where ϕ is called the retardation or angle of *lag*, and has the value such that

$$\tan \phi = \frac{2\,\pi\,n\,L}{R}.$$

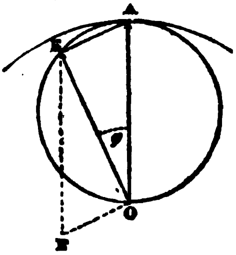
In the second term of the expression on the right-hand side of the above equation, the symbol C is a constant of integration, and ϵ is used in its common mathematical sense to represent the number 2·7182, which is the basis of the Napierian (or hyperbolic) logarithms. This second term may be omitted, because it relates only to the irregularities during the first starting of the current, and dies out as the time t increases in value. We have, therefore, got our equation for the current as follows:—

$$i_\theta = \frac{D \cos \phi . \sin (\theta - \phi)}{R}; \qquad [\text{VIII.}]$$

which should be compared with the value that the current would have if there were no self-induction, as given in [VI]. We see by comparing the two expressions that our current still follows a sine-function, but it is the sine-function not of the angle θ, but of the angle $(\theta - \phi)$; that is to say, its waves *lag* behind those of the impressed electromotive-force. Also, the amplitude of the current is reduced, because everything is going on as if the amplitude of the impressed electromotive-force had been altered from D to D $\cos \phi$. Or, in other words, the effective electromotive-force is equal to the part of the impressed electromotive-force as resolved along the line of the lagging current.

Geometrical Treatment.—Another mode of studying these rather complex relations is by the aid of the diagram explained above. First let it be understood how if the current is undergoing periodic changes, its rate of change (to which the self-induced reactions are proportional) will also undergo periodic change, but with the difference that the waves of self-induced electromotive-force will lag exactly a quarter-period behind those of the current, or will be "in quadrature"[1] with them; for the rate of change of the sine is proportional to the cosine, and the cosine is simply the sine shifted on a quarter of a revolution. Hence, when using in diagrams, a circle of revolution, as in Figs. 395 or 396, we have a line in any position representing the current or the effective electromotive-force which generates it, the line which is to represent the self-inductive reaction must be drawn at right angles—in quadrature—to the current. Let O A in Fig. 397 represent the amplitude of the impressed electromotive-force. Describe a circle upon O A, and on this circle take a point E, so that angle A O E $= \phi$, and join A E, O E. A E O will be a right angle, and A E will represent the magnitude of the electromotive-force of self-induction when O E represents the current, or the effective electromotive-force which produces the current; the whole being considered to revolve about O, and the projections on the vertical line being taken as explained above. We have here two electromotive-forces, the impressed O A and the reactive A E (or O F, which is equal to it), with their resultant the effective electromotive-force O E, with an angle E O A, or ϕ between them; the effective electromotive-force being equal to the impressed electromotive-force multiplied by cos ϕ. Let us now examine this angle ϕ which represents the lag of the effective electromotive-force (and therefore of the current) behind the impressed electromotive-force. We know that O E is equal to R i, and A E is equal to $2\pi n$ L i, being the maximum value of the rate of change of L i cos θ

Fig. 397.



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[1] This use of the term is due to Mr. Blakesley, *op. cit.*

(i. e, the maximum value of $2\pi n L i \sin\theta$). That is to say, A E is to O E as $2\pi n L$ is to R. Or,

$$\tan\phi = \frac{2\pi n L}{R}.$$

The quantity $2\pi n L$ is sometimes called the *inductance*, so that we may say the angle of lag is such that its tangent depends on the ratio of the *inductance* to the resistance. If we draw the triangle separately, as in Figs. 398, we may mark the values of the sides, the hypotenuse becoming $\sqrt{R^2+4\pi^2 n^2 L^2}$, a quantity sometimes called the "apparent resistance," or sometimes the "impedance."[1] We see then that $\cos\phi$ is equal to $R \div \sqrt{R^2+4\pi^2 n^2 L^2}$, so that equation [VIII.] p. 627, might have been written[2]

FIG. 398*a*.

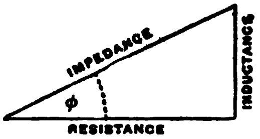
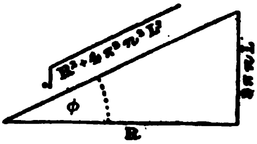


FIG. 398*b*.



$$i_\theta = \frac{D\sin(\theta-\phi)}{\sqrt{R^2+4\pi^2 n^2 L^2}}; \qquad \text{[IX.]}$$

where we write the whole impressed (and retarded) electromotive-force as numerator, and the impedance as denominator,[1] instead of writing the effective resolved part of the electromotive-force as numerator, and the true resistance as denominator.

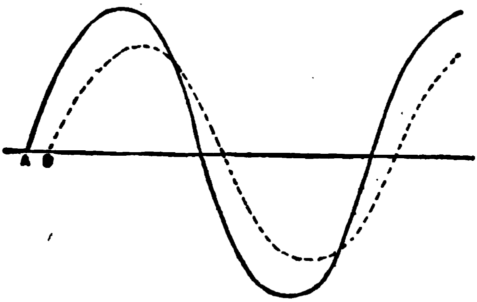
---

[1] The term *impedance* strictly means the ratio of any impressed electromotive-force to the current which it produces in a conductor (see Lodge's *Modern Views*, p. 398), of which the above is only one case. For steady currents the impedance is simply the resistance. For variable currents it may be made up of resistance, inductance, and (if the circuit has electrostatic capacity), of permittance, in various proportions according to the *form* of the variation. For true periodic currents obeying the sine-law the impedance is the square root of the sum of the squares of resistance and inductance. For currents which vary more suddenly the impedance will depend more on self-induction and less on resistance.

[2] This is indeed the classical way of writing it ; and it was so written in the previous editions of this work. The whole notion of an apparent resistance, partly made up of real resistance and partly made up of an inductive reaction, is, however, awkward. The inductive reaction is not of the nature of a resistance, but that of an electromotive-force, which, compounded with the impressed electromotive-force, gives us a nett effective electromotive-force.

Before leaving Fig. 397 and the angle of lag, we may note that the lag is proportional both to L and to n; so that raising the frequency of alternations will exaggerate the two inductive reactions—will increase the lag and diminish or damp down the current. But increasing the resistance, though it diminishes the current, tends to lessen the lag. The effect of self-induction is then to *retard* the rise and fall of the current, so that it attains its maximum not when $\theta = 90°$, but when $\theta = 90° + \phi$, and ϕ cannot in any case exceed 90°, as will be seen by considering Fig. 397. Further, both the inductive reactions will increase with increased speed. There will be less lag, therefore, if the machine is so designed that it can be driven at a slow speed, or if the number of alternations per second be diminished, and if the coefficient of self-induction is small compared with the resistance of the circuit. This indicates that the number of turns of the coils in the armature part should be kept as small as possible, and the magnetic field made enormously powerful—a rule which applies equally to continuous-current dynamos.

FIG. 399.



These two inductive reactions, the lag and the damping of the current, may be summed up in a diagram, Fig. 399. Let the curve A represent the rise and fall of the induced current, as it would be if there were no self-induction. Then, since the tendency of self-induction in the circuit is both to retard the rise and fall of the effective electromotive-force, and to damp it down, it will have the effect of causing the current to rise and fall like the curve B, which has a smaller amplitude and is shifted along.

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[1] See Maxwell, *Phil. Trans.*, 1865, p. 473.

It may be remarked that mere retardation does not waste any of the power, nor does the mere introduction into the circuit of the opposing electromotive-forces of self-induction. If induction could be limited to these two effects, it would not be very prejudicial, it would simply make the machine act as a smaller machine. It lowers the plant-efficiency, but not the running-efficiency.

"*Virtual*" *Electromotive-force.*—Alternate-current voltmeters and alternate-current amperemeters do not measure the true average values of the volts and of the amperes. They measure what are called "virtual volts" and "virtual amperes." In a Cardew voltmeter the heating of the wire depends on the square of the current. In an electro-dynamometer the torque depends at every instant on the product of the currents in the fixed and movable parts; therefore, when used as an amperemeter, depends on the square of the current. The readings which these instruments give us, if first calibrated by using steady currents, are not true means, but are the square roots of the means of the squares. Now the mean of the squares of the sine (taken over either one quadrant or a whole circle) is $\frac{1}{2}$; hence the square-root-of-mean-square value of the sine functions is got by multiplying their maximum value by $1 \div \sqrt{2}$, or by 0·707. But we have seen that the arithmetical mean of the values of the sine is 0·637. Hence an alternating current, if it obey the sine law, will produce a heating effect greater than that of a steady current of the same average strength, by the ratio of 0·707 to 0·637; *i. e.* about 1·1 times greater. If a Cardew voltmeter is placed on an alternating circuit in which the volts are oscillating between maxima of + 100 and − 100 volts, it will read 70·7 volts, though the arithmetical mean is really only 63·7; and 70·7 steady volts would be required to produce an equal reading. The term *virtual*[1] has been used to denote these square-root-of-mean-square values. It may be remarked in passing that the virtual electromotive-force of a dynamo wound for alternate currents will therefore be 2·2 times higher (compare p. 651) than that of the same dynamo wound as an ordinary direct-current dynamo. The equations established above hold good, whether maximum or virtual values are used. For example, we may write

$$\text{Maximum } i = \frac{\text{maximum E}}{\text{resistance}} \times \cos\phi;$$

$$\text{Maximum } i = \frac{\text{maximum E}}{\text{impedance}};$$

or

$$\text{Virtual } i = \frac{\text{virtual E}}{\text{resistance}} \times \cos\phi;$$

$$\text{Virtual } i = \frac{\text{virtual E}}{\text{impedance}}.$$

The diagrams of revolving lines may be drawn either with maximum or virtual values.

Mean Power.—The mean power is obtained by integrating the power during one period and dividing by that period, and therefore may be written

$$\frac{1}{T}\int_0^T E\, i\, dt = \frac{1}{T}\int_0^T R\, i^2\, dt = \frac{1}{T}\int_0^T \frac{E^2}{R}\, dt.$$

Now if E and i were always in the same phase, the power at any moment would be simply the product of their values at that moment, and the mean power would be the product of their virtual values, or the half of the product of their maximum values.[1] But if there is a lag ϕ between them, then the product at each instant must be multiplied by cos ϕ. So that

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[1] I adhere to the term *virtual;* it was in use before the term *effective* which was recommended in 1889 by the Paris Congress to denote the square-root-of-mean-square value. I adhere to it mainly because the adjective *effective* is required in its usual meaning in kinematics to represent the resolved part of a force which acts obliquely to the line of motion, the effective force being equal to the whole force multiplied by the cosine of the angle at which it acts with respect to the direction of motion.

$$\begin{aligned}\text{Mean power} &= E_{\text{virt.}} \times i_{\text{virt.}} \times \cos\phi, \\ \text{,,} \quad \text{,,} &= \tfrac{1}{2} E_{\text{max.}} \times i_{\text{max.}} \times \cos\phi, \\ \text{,,} \quad \text{,,} &= i^2_{\text{virt.}} \times R, \\ \text{,,} \quad \text{,,} &= E^2_{\text{virt.}} \div R.\end{aligned}$$

If we square the expression [IX.] found for current and substitute for the square of the sine its mean value $\frac{1}{2}$, and then multiply by R we get as the mean power (in watts)

$$W = \frac{2\pi^2 n^2 S_2^{\,2} N^2 R}{R^2 + 4\pi^2 n^2 L^2};$$

and this expression, by a well-known algebraic rule, will be a maximum for variations of R when R is such that the two terms in the denominator are equal, or when the resistance equals the inductance. Under these circumstances the lag is 45°. But though this is the condition for highest plant efficiency, the regulation is, under these circumstances, bad. Hence it is better to use such a machine for lesser currents than those which would produce so great a lag.

Numerical Example:—Let an impressed electromotive-force of 65 (virtual) volts, alternating with a frequency of 50 periods per second, act upon a circuit having resistance 1·5 ohm, and a coefficient of self-induction of 0·002 henry. Find the lag, the current and the mean power.

To find the lag, we must find the inductance, $2\pi n L$, and divide this by the resistance; or

$$\tan\phi = 2\pi n L \div R = 2 \times 3{\cdot}1416 \times 50 \times 0{\cdot}002 \div 1{\cdot}5 = 0{\cdot}419.$$

Looking in a table of natural tangents, we find that ϕ will be 22° 44′; whence a table of natural cosines gives us cos ϕ =

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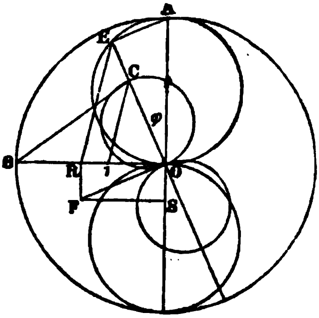
[1] On the question of measurement of the mean power of alternating currents, see papers by Prof. Ayrton and others in *Phil. Mag.* and in *Proc. Roy. Soc.* in 1891, copied into most of the technical journals; also papers by Swinburne and Blakesley. Blakesley's method of the three electrodynamometers, and Ayrton's method of the three voltmeters, ought to be known to every person who requires to measure power in alternate current circuits and machines.

0·9223. Or, we might calculate cos ϕ directly as $R \div \sqrt{R^2 + 4\pi^2 n^2 L^2}$. Multiplying cos ϕ into the 65 volts, we get 59·95, say 60, as the effective virtual volts, and dividing by the resistance, gives 40 virtual amperes as the current. The mean power is $65 \times 40 \times 0{\cdot}9223 = 2400$ watts.

Geometrically this is given in Fig. 400.

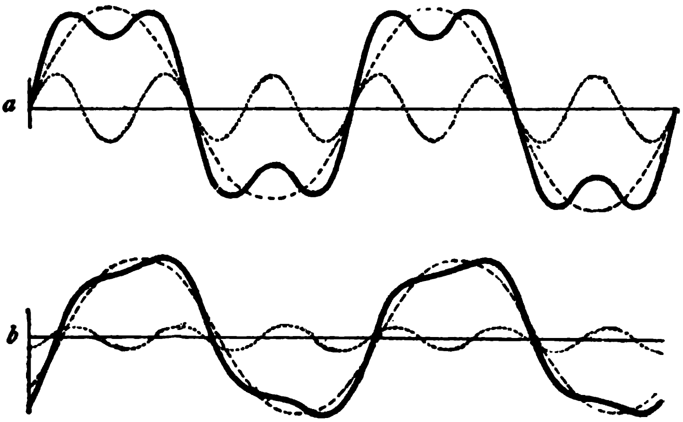
Let O A be 65 to any scale, the impressed (virtual) volts. Describe the circle of radius O A, and the semicircle O E A. Draw O B at right angles to O A. On O B set off O R on any convenient scale of resistance, O 1 being taken as 1 ohm. Using same scale, set off O S or R F at right angles, equal to the inductance $2\pi n L = 0{\cdot}628$. Join O F. R O F is the angle of lag. Draw E O at right angles to O F, cutting semicircle in E. E O A is also angle of lag, hence E O represents effective virtual volts; and A E the cross-electromotive-force of self-induction $2\pi n L i$. Join E R and from 1 draw 1 C parallel; C O will represent the current. As O B is O A turned through a right angle, the area of triangle B O C = ½ O A· O C· cos A O C = ½ mean power.

Fig. 400.



We are now in a position to explain why it is desirable that the induction curves of alternators should follow the sine-form, and why wide departures therefrom are undesirable. According to the well-known theorem of Fourier, every complex single-valued periodic function can be analyzed down into a series of simple periodic functions differing in amplitude and phase, but all belonging to a harmonic series, having frequencies that are some exact multiple of a single fundamental frequency. Every complex wave curve may be regarded as built up of sine-curves. For example, the curve shown in Fig. 401*a* may be looked upon as a compound of the two dotted sine curves, one of a frequency three times that of the other. Now, if this complex curve represents the impressed electromotive-force of an alternator with curiously-shaped poles, what will the curve of effective electromotive-force (or of current) be when self-induction is present? The amplitude is cut down in proportion nearly to the frequency of the alternation. Hence the component ripple, which has three times the frequency, will be damped out nearly three times as much as the fundamental wave.[1] In Fig. 401 *b* are shown the two waves, as altered by a lag of 41°, which cuts down the fundamental to 0·75, and the ripple to 0·35 of their respective amplitudes; the resultant wave being also shown. It is evident that self-induction tends to smooth out the ripples, including all parts of the wave that do not fit to the sine form. Hence those

FIG. 401.



alternators which give induction curves of true sine form are less affected by self-induction than others, regulating better, and having a higher plant-efficiency.

Alternate Currents in relation to Capacity.—If a condenser is interposed in the circuit of an alternator, an alternate current will play into and out of the condenser, charging it in alternate directions. The action of the condenser's capacity on the current is best summed up by saying that it acts like a negative and reciprocal inductance. If K be the capacity of the condenser (in farads), and the frequency be n, then it will act like a (negative) inductance of $-1 \div 2\pi n$ K henries. The effect, therefore, of a capacity in series with the circuit, is to accelerate the phase of the current, producing a lead instead of a lag in the current. A capacity acting laterally across the circuit, as when a condenser is placed across the two mains, has the effect of increasing the flow of current from the dynamo up to the points on the circuit which are connected to it, and therefore of raising the virtual potentials of those points, thereby affecting the voltage of the rest of the circuit. There is, for a given frequency, resistance and self-induction, one particular value of capacity which would enormously increase the current and voltage as by a sort of resonance. These various condenser effects have been considered by various writers. A very clear exposition of them, together with the phenomena observed on the Ferranti mains on the Deptford supply has been given by Fleming.[1]

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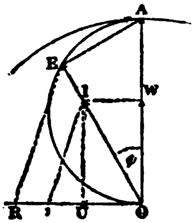
[1] See investigation by Ayrton and Perry in *Journal Inst. Electrical Engineers*, xviii. 300, 1889.

Watt-less Current.—Whenever there is a great phase difference between volts and current (whether a lag due to self-induction or a lead due to capacity), the true watts are, as has already been pointed out, much less than the apparent value that would be obtained by merely multiplying together the virtual amperes and the virtual volts. For, as we have seen, this product must be further multiplied by the cosine of the angle of lag (or lead). Now there are two ways of looking at this matter, the product $E_{\text{virt}} \times i_{\text{virt}} \times \cos\phi$ may be regarded as either the product of the virtual amperes into the resolved part (or effective part) of the virtual volts, or it may be regarded as the product of the virtual volts into the resolved part of the virtual amperes. Just as any force may be resolved into two component forces at right angles to one another, so any alternating current may be resolved into two component alternating currents differing 90° in phase. Or i may be resolved into two parts, $i\cos\phi$ agreeing in phase with the volts, and $i\sin\phi$ in quadrature with the volts. These two resolved parts of the current may be termed the *working-current* and the *watt-less current*. In Fig. 402 O E represents the effective part of the impressed electromotive-force O A. Of O E a part O I is found, as described on p. 634, to represent the current i. Of this current the resolved part O W, in phase with O A, is the working current, and the part O U, which is in quadrature with O A, is the watt-less current. Whenever, for either cause, the angle of lag is great, the watt-less part of the current will be great also. For example, when

FIG. 402.



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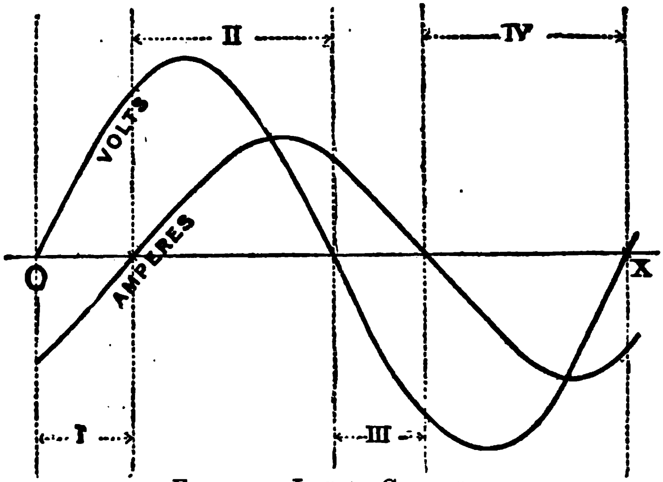
[1] *Journal Inst. Electr. Engineers*, xx. 362, 1891.

transformers are left on open circuit, the current in the primary is nearly in quadrature (owing to self-induction) with the impressed volts, and, if it were not for hysteresis or eddy-currents in the iron cores, would be almost entirely watt-less.

For example, if there is a current of 100 virtual amperes lagging 14° behind the impressed volts, this may be resolved into a working current of 97·03 virtual amperes, and a watt-less current of 24·2 virtual amperes.

High Frequency Alternations.—Alternations of very high periodicity, going up to as many as 10,000 or 20,000 per second, have been studied by Spottiswoode,[1] and more recently by Tesla,[2] who has obtained some very remarkable effects. One of his alternators was of the same type as Mordey's, having numerous polar projections on either side,[3] and another was of the inductor type. With these excessively high frequencies the currents flow almost exclusively along the surface layers of conductors, instead of flowing through their entire cross-section; even straight rods of copper offering a relatively enormous impedance.

FIG. 403.



EFFECT OF LAG OF CURRENT.

Torque of Alternators.—A very singular result follows the presence of any lag in the current of an alternator. It was pointed out on p. 554, that where amperes flow with the volts, electric energy is being supplied by the machine, and power must be applied to drive it; but that when amperes flow against a counter electromotive-force, there electric energy is leaving the circuit and being turned into mechanical energy, helping to drive the machine. The one is the case of the generator, the other that of the motor. But now consider an alternator with the amperes lagging behind the volts, as indicated by the diagram of Fig. 403. It is clear that in consequence of this lag the amperes are sometimes flowing against the volts instead of with them. In fact, we may divide each complete period such as O X into four parts, during two of which, namely II. and IV. in Fig. 403, the amperes and volts are alike in direction, either both positive, or else both negative; during the other two parts—namely I. and III.—the amperes and volts are opposed in direction because the volts have reversed in sign, but the lagging amperes have not yet changed. Now during the partial periods II. and IV., when there is agreement in sign, the machine is in the condition of being a generator, and will require to be driven, the currents in the armature setting up a counter torque. But during the other partial periods I. and III., when there is opposition in sign, the machine is in the condition of being a motor, and will tend to drive itself, the torque helping it on. The conductors are consequently subjected to a racking action, alternately resisting, being driven and then helping to drive twice in each period. It is clear that if there is little lag there will be little motor action, the partial periods I. and III. being brief; whereas if there is much lag the motor action will increase. If there is a lag of exactly a quarter of a period, the motor and generator actions will be equal. Similarly, if in consequence of capacity the current leads in phase, there will be motor action in partial periods. This subject may be considered in another way. The electromotive-forces change sign just as the conductors are passing (for example, take Fig. 412, p. 646) from one magnetic field into another, where the lines run in an opposite direction. If the currents are in phase with the electromotive-forces, they will always tend to oppose the motion that generates them. But if they lag then after the conductor has passed from one field to the other until such time as the currents have reversed, they will be helping on the motion.

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[1] *Proc. Roy. Soc.*, xxiii. 455.

[2] *American Inst. Electrical Engineers*, May 1891. See *Electrical World*, xvi., 1891, and *The Electrician*, xxvi. 549, 1891.

[3] See *Electrical Engineer* (N. Y.), March 18, 1891.

Measurement of Power in Alternating Circuits.—On this important topic see remarks on p. 633.

CHAPTER XXIII.

ALTERNATORS.

ALTERNATORS, or alternate-current dynamos, may be classified in three sorts :—

I. Those with stationary field-magnet and rotating armature.

II. Those with rotating field-magnet and stationary armature.

III. Those with both field-magnet part and armature part stationary, the amount of magnetic induction from the latter through the former being caused to vary or alternate in direction by the revolution of appropriate pieces of iron, called *inductors*.

Alternators may also be classified according to whether they give simple two-phase currents, or are multiphase.

In all alternators the electromotive-force rises and falls in a rapid periodic fashion, a wave of electricity being forced through the circuit, first in one direction, then in the other, with very great rapidity. The time taken for one complete alternation to-and-fro of the current is called one *period*. The number of such complete periods or double-reversals of the current in a second is called the *frequency*, or sometimes the *periodicity*, of the alternations. The frequency used in practice varies between 40 periods per second to 100 or sometimes 150 periods per second; but each machine is expected to work at its own proper frequency. The symbol ∼ is sometimes used for the frequency instead of the letter *n*. Thus, 100 ∼ stands for a frequency of 100 complete periods per second, *i. e.* 100 positive currents or half-waves, each followed by a negative half-wave. The symbol *n* used for the number of revolutions per second in the formulæ for direct-current dynamos is also used for the number of periods per second in formulæ for alternate currents; as it corresponds to the number of complete alternations there would be if the dynamos had but one pair of poles. As it is requisite in alternate-current working to have so many alternations in every second, and as mechanical considerations forbid very high speeds, it is the general practice to make this class of machines multipolar, with a considerable number of poles of alternate polarity arranged symmetrically around a common centre. The number of symmetrical poles in machines of different systems varies from 12 to 48, or more.

The armatures of alternators may be of ring, drum, pole, or disk type; but in all cases the grouping of the windings is different from that which would be adopted for a direct-current dynamo. The field-magnet being multipolar, a section of the armature winding which is passing a N-pole will have currents induced in it that circulate in an opposite sense to those induced in a section which is at the same moment passing a S-pole. Hence in an alternate-current ring the successive sections must be either wound or connected so as to be alternately right-handed and left-handed. In alternate-current drums the sections do not overlap one another as in ordinary drum armatures; nor do they overlap in alternate-current disk armatures.

Ring Armatures.—This type was invented in 1878, almost simultaneously by Gramme[1] and by Wilde,[2] the main difference between them being that, whilst Gramme rotated his field-magnet within a large stationary ring, Wilde rotated his ring armature within an external system of inwardly pointing field-magnet poles (see Fig. 120, No. 28). When ring armatures are used in this type of dynamo, they must not be wound in the same manner as for continuous-current armatures. If the successive sections are to be connected up consecutively, then they must be wound, as shown in Fig. 404, alternately with right-handed and left-handed windings. If all the sections are coiled right-handedly, then they must be connected, as shown in Fig. 405; for the electromotive-force induced in a coil as it passes under a north pole will circulate around the armature core in an opposite direction

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[1] Specification of Patent, 953 of 1878.

[2] Ibid., 1228 of 1878.

Fig. 404.

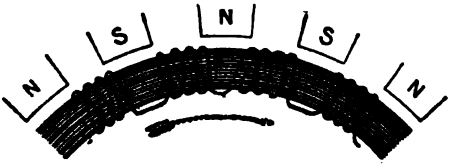
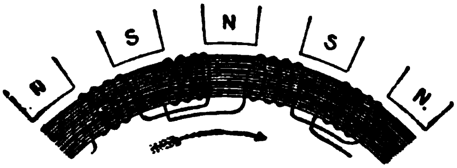
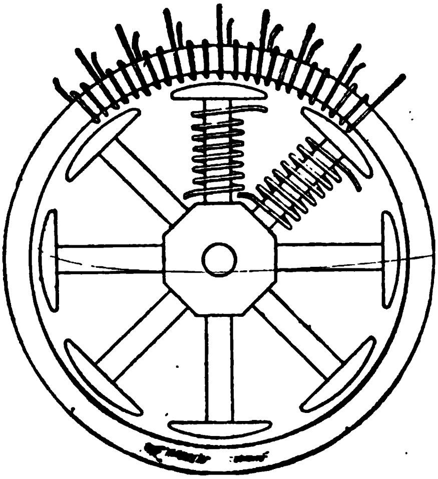


Fig. 405.



Ring-Armature Windings for Alternators.

Fig. 406.



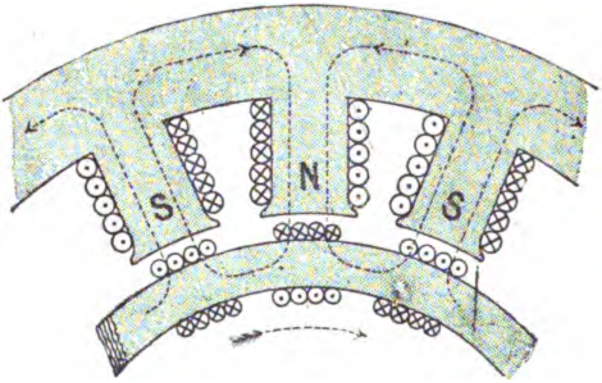
Gramme Alternator.

to that induced in the neighbouring coil that is passing under a south pole.

A diagram of the Gramme alternator is shown in Fig. 406.

The sections of the winding of this machine were four times as numerous as the poles, and might be coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. One form of Gramme alternator, designed for use with Jablochkoff's candles, and made auto-exciting by the addition of a small direct-current dynamo on the same shaft, was depicted in the former editions of this book. Another ring alternator, by De Meritens, with permanent steel magnets was a favourite about 1879. Another design, with external magnet, is shown in Fig. 407, which closely resembles the form used by Messrs. Ernest Scott and Mountain. In this figure, the magnetic circuits are traced to guide the designer in calculating out the exciting power. It will be noticed that the inner wires of the ring perform no active inductive part; also that the currents in adjacent sections flow reversely.

FIG. 407.

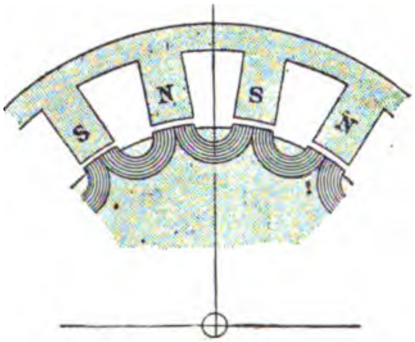


MAGNETIC CIRCUITS OF ALTERNATOR.

In Kapp's alternator, Fig. 421, p. 655, the ring lies between a double crown of field-magnet poles. Other ring alternators have been designed by Kennedy, who uses a discoidal ring between alternately-spaced alternate poles within an iron-clad magnet; and by Mordey who has suggested a form with two Pacinotti rings, one laminated as armature, one non-laminated, as field-magnet.

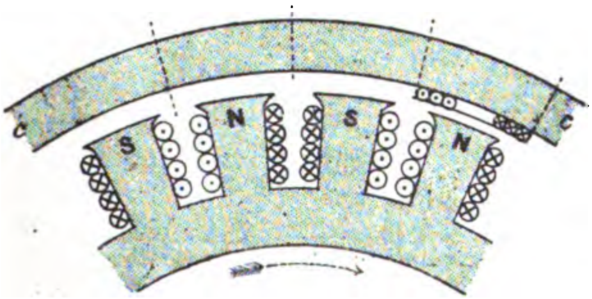
Drum Armatures.—A glance at Fig 407 will show that, so far as the active wires are concerned, they might be coupled up quite as effectively without being wound around a ring core. In Fig. 408, which is a diagrammatic picture of the Westinghouse alternator, the windings lie on the outside of a drum-core; the sections being coiled separately on temporary frames and then laid upon the surface of the core, with the ends turned down over the end core disks and firmly secured.

Fig. 408.



Westinghouse Alternator.

Fig. 409.

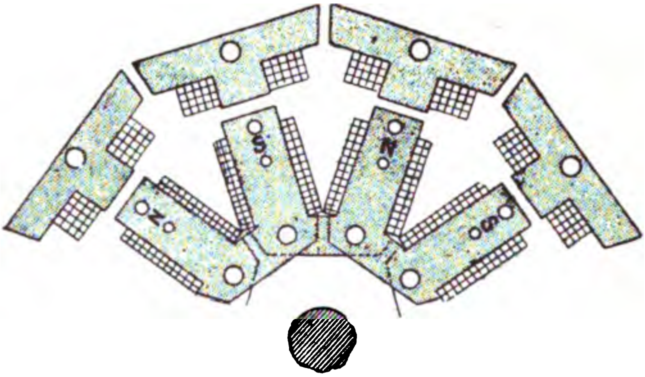


Elwell-Parker Alternator.

It is but a step from this form to that of Fig. 409, which has an internal revolving field-magnet, and as armature an external cylinder built of segmental core-plates, against the inner periphery of which the armature coils are fastened.

Again, it is but a step from this form to Fig. 410, which shows the construction of Zipernowsky, in which the field-magnet cores are made up of U-shaped stampings, and the armature cores of short T-shaped pieces which project through the coils, and are removable singly. We are thus passing away from the drum type toward that with pole armature.

FIG. 410.

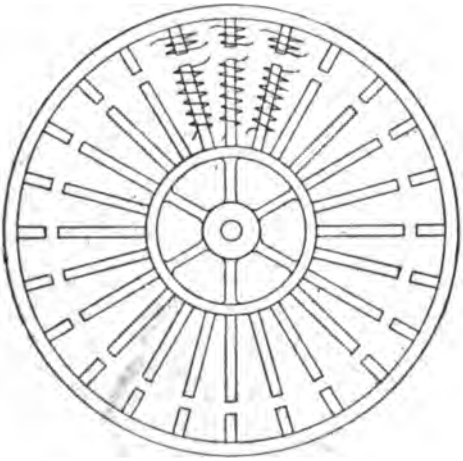


GANZ-ZIPERNOWSKY ALTERNATOR.

Pole-Armatures.—The typical pole-alternator is the now obsolete machine of Lontin, a skeleton diagram of which is given in Fig. 411. In this machine the field-magnet (separately excited with a continuous current) consisted of a set of radiating poles, and it rotated within an outer set of coils which served as a fixed armature. These coils were wound upon short cores of solid iron. This machine had many defects, not the least of which was the great mass of iron in which so many internal eddy currents were induced that the machine was very prone to become overheated. Indeed, it required more power to drive it on open circuit than when the machine was supplying its maximum number of lamps.

A modification of this machine, having laminated iron cores in the armature part, has been used by Kennedy and others. Hopkinson's alternator, Fig. 425, p. 664, is an inversion of this design, the field-magnet being fixed and external.

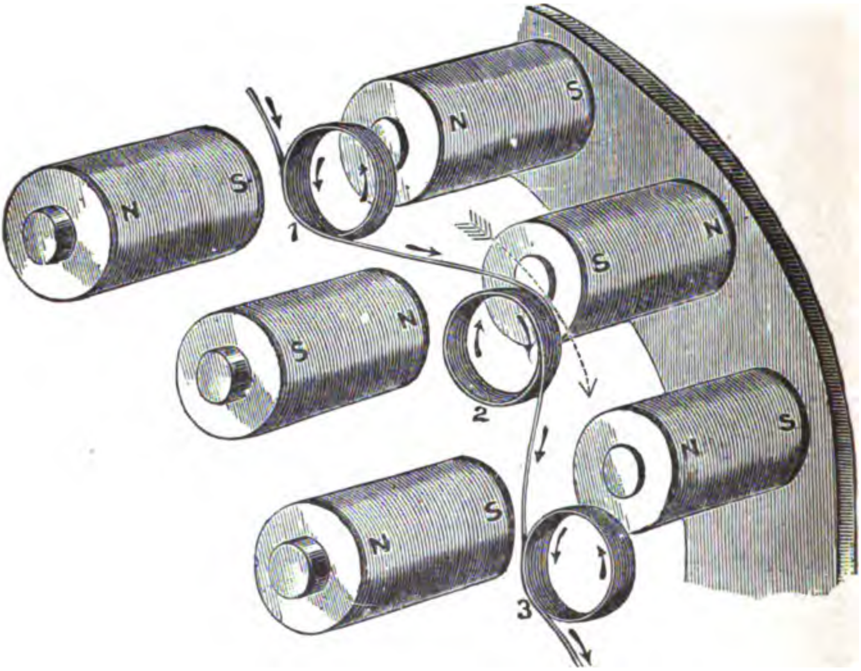
FIG. 411.



PRINCIPLE OF POLE ALTERNATOR.

Disk Armatures.—In these machines the armature coils are arranged around the periphery of a disk. The old machines of Nollet and Holmes, and the so-called "Alliance" machine (all of which had permanent magnets of steel), belonged to this class. The more modern type, with electro-magnets, was created by Wilde, in 1867. The field-magnets consist of two crowns of fixed coils, with iron cores arranged so that their free poles are opposite to one another, with a space between them sufficiently wide to admit the armature, Fig. 412. The poles taken in order round each crown are alternately of N and S polarity; and opposite a N-pole of one crown faces a S-pole of the other crown. This description will apply to the magnets of the alternate-current machines of Wilde and Siemens, and to Ferranti's alternator. The principle will be best understood by reference to Fig. 412, which gives a general view of the arrangement. Since the magnetic lines run in opposite directions between the fixed coils, which are alternately S—N, N—S, as described above, the moving coils will necessarily be traversed by alternating currents; and as the alternate coils of the armature will be traversed by currents in opposite senses, it is needful to connect them up, as shown in Figs. 416 or 417, so that they shall not oppose one another's action. In Wilde's alternator, the armature coils had iron cores, and the machine was provided with a commutator on the principle indicated in Fig. 419, p. 652. This commutator Wilde usually applied to a few, or only one, of the rotating coils, and utilized the current thus obtained to magnetize the field-magnets. The two contact-rings for collecting the main current are also shown in the figure.

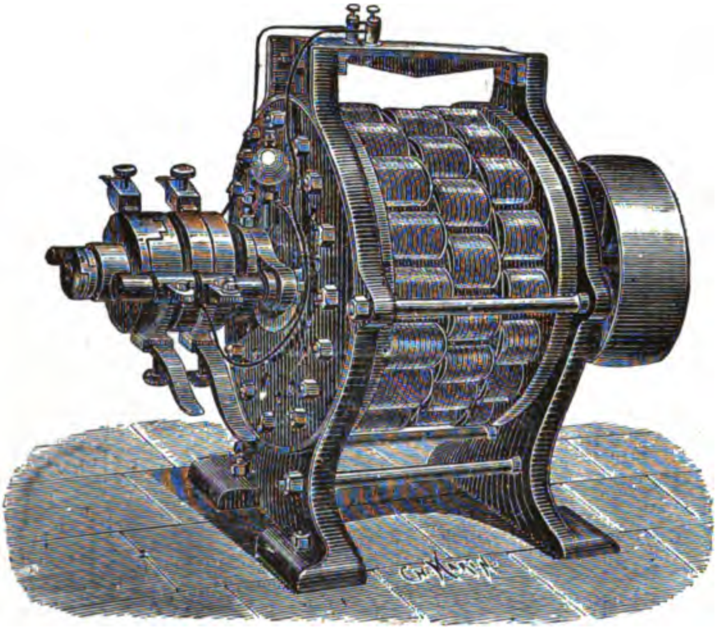
FIG. 412.



PRINCIPLE OF DISK ALTERNATOR.

Siemens improved the design in 1878, by omitting the iron from the cores of the armature, which he narrowed greatly, thus diminishing its reactions. Ferranti's alternators follow

FIG. 413.



WILDE'S ALTERNATOR.

FIG. 414.

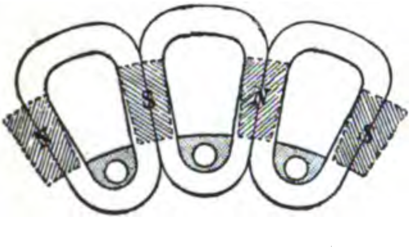
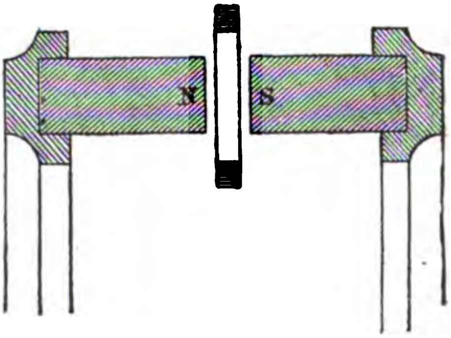


FIG. 415.

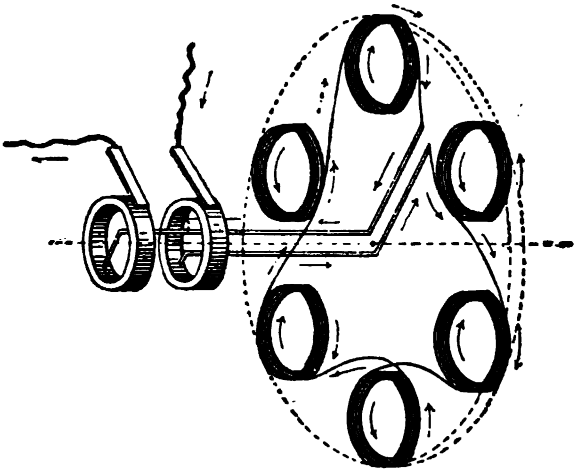


FERRANTI'S ALTERNATOR.

the same plan, the copper coils being built up into a thin disk, as indicated in Figs. 414 and 415.

Collecting-Rings.—For collecting the main current of the alternator, extremely simple means are required. In those machines in which the armature part is fixed, mere terminals are required. In machines with rotating armatures simple sliding connexions are required. The usual method of collecting is shown in Fig. 416. Two undivided insulated metal rings, forming the terminals of the armature coil, slide each under a single collecting-brush.

FIG. 416.

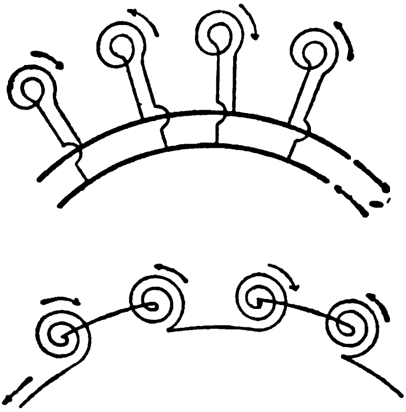


COLLECTING-RINGS OF ALTERNATORS.

Where high voltages are used the two contact rings should be so placed that by no accident can an attendant touch both at the same time. It is also well to provide two brushes to each ring. For alternators with stationary armatures a similar but smaller pair of contact-rings suffice to carry the exciting current to the revolving field-magnets. The special devices of Ferranti for collecting are described later.

Coupling Armature Coils.—There are various ways of coupling up the coils of alternators, according to their purpose. For low voltage work the coils may be coupled up in parallel as in Fig. 417, so as to reduce the internal resistance; whilst for supplying distant transformers and for transmission of power, in both of which cases high electromotive-force is required, the more usual mode of connecting is to join the several coils in series, as in Figs. 416 and 418. In Chapter XII., on the theory of armature winding, it was shown (see Figs. 202 and 203) how either a lap-winding or a wave-winding might be applied to an alternator. The use of a wave-winding for this purpose was suggested almost simultaneously in 1881, by Sir William Thomson, and by Mr. Ferranti. But there are disadvantages in its use for high voltages, owing to the difficulty of maintaining the insulation between each "wave" and the succeeding one, and it has been abandoned in favour of a lap-winding, in which each coil can be well insulated by itself from its neighbours. In some alternators—including those of Ferranti and Westinghouse—the coils are joined in two parallels, not all in series, a construction which has the result of keeping the points of greatest potential difference widely apart.

FIGS. 417, 418.



DIFFERENT MODES OF COUPLING UP ARMATURE-COILS OF ALTERNATORS.

WIDTH OF POLE FACES AND BREADTH OF ARMATURE WINDINGS.

The distance from the centre of one N-pole to that of the adjacent S-pole may be called the *pitch* of an alternator. It is desired to know what is the best proportion for the pole-faces and the windings to bear to the pitch. This matter has been discussed by Kapp.[1] It involves two questions—(1) in what way will the voltage depend on the relative width of poles and breadth of windings; (2) what proportions will give the highest plant-efficiency. If the poles are too wide, so as nearly to touch, not only is there great leakage, but the coils must be inconveniently crowded. It is obvious that for any coil to give its best result it should be so large as to embrace the whole flux of magnetic lines from each pole as it passes. If it is smaller, it contributes less to the total voltage. If it is larger it merely takes more space. Hence it is usual to make the width of the internal aperture of the coils but little less than the width of the pole, and to make the external width equal to the pitch. Compare Figs. 407, 408, and 409, in the first two of which the inner width is rather less, and in the third rather greater than that of the pole-faces, whilst the double breadth of copper in the coils is about equal to the width of the poles.

It has been shown on p. 211 that the average electromotive-force of a continuous current dynamo may be written

$$E = n \, C \, \mathbf{N} \div 10^8;$$

where n was the number of revolutions per second, C the number of conductors around the armature, and $\mathbf{N}$ the magnetic flux. We may adapt this to alternators, whilst keeping the two former symbols, and using $\mathbf{N}$ for the magnetic flux through any *one* pole, by multiplying by p the number of pairs of poles, and by a coefficient k.

So we have

$$E \text{ (virtual volts)} = k \, p \, n \, C \, \mathbf{N} \div 10^8.$$

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[1] *Proc. Institution Civil Engineers*, xcvii. 1889, pt. iii.

If the fluctuations follow a sine curve, so that the virtual volts are 1·1 times greater (see p. 631) than the average volts, the coils are all joined in series (instead of two parallels), and *k* will have the value 2·2. The value of *k* for various widths of poles and breadths of coils has been calculated by Kapp, with following results:—

Pole width.	Total breadth of Copper in Coil.	*k*
1. Equal to pitch	Equal to pitch (covering whole surface)	1·160
2. Equal to pitch	Half of pitch (covering half surface)	1·635
3. Half of pitch	Equal to pitch (covering whole surface)	1·635
4. Half of pitch	Half of pitch (covering half surface)	2·300
5. Third of pitch	Third of pitch (covering third of surface)	2·830

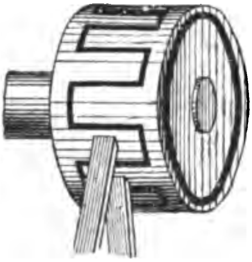
If there were no spreading of the magnetic field, No. 4 of these would be best (being also nearest sine-law). The useful breadth of wires is that which would just lie between the pole-tips. The output of a machine having a given thickness of copper in the gap is proportional to the number of such wires to width of the pole-face; therefore to the product of the two breadths, the sum of which, if there were no magnetic spreading, would equal the pitch. Hence the output would be a maximum when the breadth of coils and width of poles were each half the pitch. But Elihu Thomson has found by experiment that, owing to the distortion of the magnetic field when the machine is running, there is an advantage in making the breadth of copper greater than this, that is by diminishing the aperture of the coils to something less than one-half the width of the pole-face.

There has been much controversy whether armatures should or should not have iron cores. Iron cores are certainly inadmissible in thin disk armatures, as they would inevitably jamb against the pole-faces. Owing to the high frequency of alternation, the loss by hysteresis in machines with iron cores becomes serious, unless the magnetization is kept down below 7000 lines per sq. cm., and even then is not negligible. On the other hand, there is more loss by eddy currents[1] in the copper in machines not having iron cores.

MODES OF EXCITATION OF FIELD-MAGNETS.

In the older machines the field-magnets were either of steel permanently magnetized, or else electromagnets separately excited. About 1869 began the practice of making these machines self-exciting by the method of diverting a small current from one or more of the armature coils, which were for this purpose separated from the rest, this current being passed through a commutator, which rectified the alternations and made it suitable for magnetizing the field-magnets. Such commutators were used by Wilde and by Holmes, and have in general the form depicted in Fig. 419, consisting of two metal cylinders cut like crown-wheels having the teeth of one projecting between the teeth of the other. They are insulated from one another, one being connected to one end of the wire of the armature coils that are to be used for exciting, whilst the other is connected to the other end of that wire. Two brushes are set so that one presses against a tooth of one, whilst the other presses against a tooth of the other part. Such commutators had previously been used in small motors.[2] Holmes used a system of parallel bars (like the Gramme collector) connected together alternately into two sets. If the field-magnets are wound with fine wire, such a commutator may be used to rectify a fraction of the current from the whole of the armature coils, thus making the machine virtually a self-exciting machine. It is, however, more usual to supply each alternator with a small auxiliary continuous-current dynamo, termed its *exciter*.

FIG. 419.



COMMUTATOR FOR SELF-EXCITING ALTERNATORS.

A convenient way of regulating the current or potential of alternators is to interpose a variable resistance in the exciting circuit; the resistance being operated by hand or by some automatic regulator (see Chapter XXVII.). This method is applicable either to separately excited or to self-exciting machines. In the case where separate exciters are used, the performance of the alternator may be regulated by controlling (by variable resistances, &c.) the exciting circuit of the exciter.

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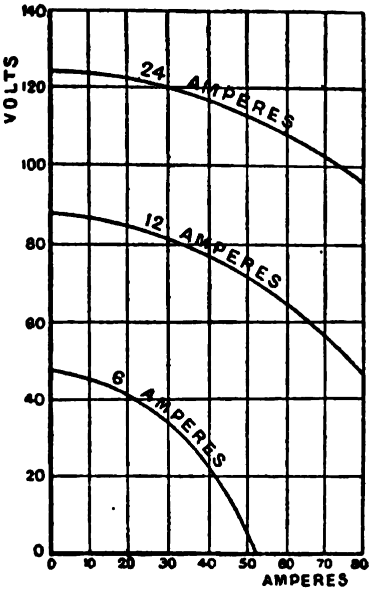
[1] See remarks by Elihu Thomson in comment on Kapp's paper, *loc. cit.*

[2] See Joule, in Sturgeon's *Annals of Electricity*. ii. 122, 1838.

Alternators, when intended for supplying ~~glow-lamps at~~ constant pressure, whether direct at low voltage, or by transformers at high voltage, are usually constructed with such low resistance in the armature part, and with so low a coefficient of self-induction, that they would be almost self-regulating if it were not for the demagnetizing influence of the armature currents. This may be considerable, and is an effect closely akin to self-induction. For supplying lamps in series with a constant current a somewhat different type of alternator is needed, having considerable self-induction in the armature. This is attained by winding the armature coils not on the outside of the core, but deeply embedded in it, or wound on long core-plates to give considerable magnetic inertia.

Fig. 420.



The demagnetizing influence of the armature current has been studied by Esson,[1] who has determined (Fig. 420) the external characteristic of an alternator when separately excited with different amounts of current. The three curves correspond to the three cases when the separate exciting current measured respectively 24, 12, and 6 amperes. The effect of the armature current is most marked when the field-magnets are weakly excited, and apparently roughly in proportion to the square of the armature current. In the Mordey alternator (p. 273) the field-magnet is so powerful that the diminution of the electromotive-force from this cause with the full current is less than 3 per cent. of the whole, the resulting droop in the characteristic being extremely slight. Swinburne[1] has also discussed armature reactions.

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[1] See *Electrical Review*, xviii. p. 248, March 1886.

Some load-curves for an alternator have been given by Kapp (*loc. cit.*), and should be compared with Fig. 287, p. 435.

Esson finds that the output of alternators may be expressed in terms of the armature dimensions and speed as follows :—

$$\text{Output (watts)} = 0{\cdot}0296\, d^2\, \text{L}\, n,$$

where d is diameter and L length, in centimetres, and n the number of revolutions per second. This is about 40 per cent. of the output of a direct-current dynamo of equal dimensions.

EXAMPLES OF ALTERNATORS.

Kapp's Alternator.—A modern alternator with ring-armature is that of Mr. Gisbert Kapp. This pattern has been constructed by the Oerlikon Machine Works, by Messrs. Goolden, and by Messrs. Johnson and Phillips. It differs from most other alternators in having double magnetic circuits. The machine depicted is a 30-kilowatt machine, having an output of 15 amperes at 2000 volts, at 700 revolutions per minute. The field-magnet consists of two crowns, of 12 poles each, alternately N and S, but each N-pole in one crown is opposite a N-pole of the other crown; so that the magnetic lines entering the ring from both faces stream laterally through the core. The armature core consists of annealed strip iron 2·5 inches (= 6·35 cm.) wide, and 0·025 inch (= 0·063 cm.) thick, which is wound up, with paper between, upon a strong foundation-ring of cast iron 28 inches (= 71·1 cm.) in diameter. The radial depth of the core is 8 inches

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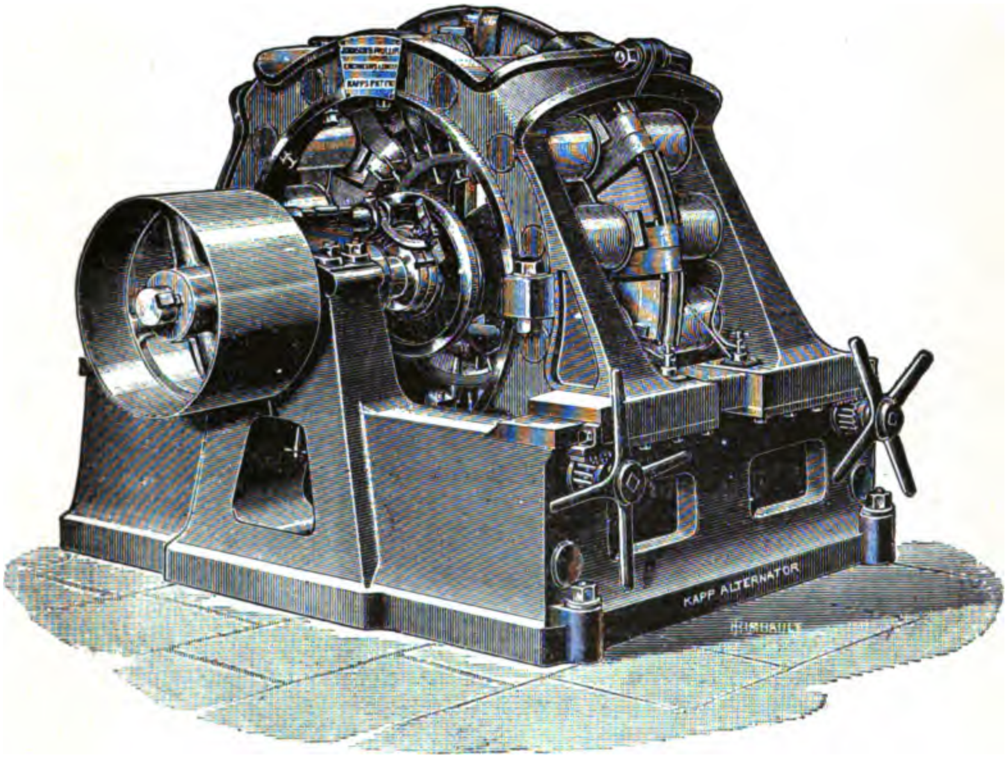
[1] *Journal Inst. Electrical Engineers*, xx. 173, 1891.

(= 20·3 cm.) and the actual cross-section of iron in it 16 square inches (= 103·2 sq. cm.). Driving-horns of ebonite are inserted at intervals, and the coils are separated from the core-iron by a liberal use of mica and paper, and are prevented from cutting at the outer edge by the insertion of a rounded

FIG. 421.



KAPP'S ALTERNATOR.

rim of mahogany. On the ring are wound twelve coils, each of a breadth a trifle less than half the pitch, and of about 100 turns each, the total number being 1190 turns. The ends are strained down through insulating bushes that pass through eyes in the foundation-ring, and are joined up to put the whole 1190 turns in series. The resistance (warm) is 7 ohms.

The 24 magnet-cores of wrought iron are each 3¾ inches diameter, having a sectional area of 11·04 square inches. They are provided with polar expansions of nearly rectangular form, about 7¼ inches by 4 inches, giving polar area of 29 square inches. The depth of polar gap from iron to iron is about 0·5 inch. The yoke-rings are of cast iron.

As self-induction in such a ring is considerable, preliminary experiments were needed to show what allowance must be made for this in the excitation. When run on short circuit, and with field-magnets separately excited to a degree that would have given the armature an electromotive-force of 1540 volts on open circuit, the armature current was 25 amperes. Hence it was concluded that when the armature current is 15 amperes, there will be a self-induced electromotive-force of 925 volts. Hence, as these will be in quadrature with the effective volts (which are desired to be about 2100), we may suppose that at the machine's full load the impressed electromotive-force will have to be

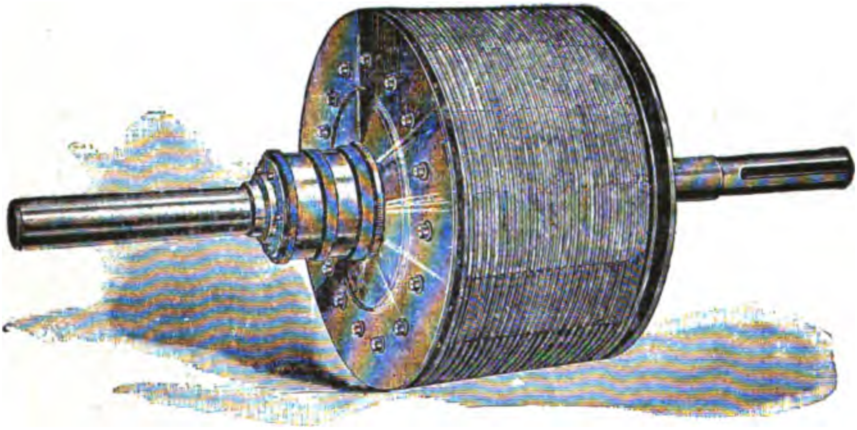
$$\sqrt{925^2 + 2100^2} = 2295.$$

Applying the formula, p. 650, and assuming $k = 2·3$, we get $\mathbf{N} = 1{,}250{,}000$ as the number that must be cut at each of the 12 poles, or 625,000 to flow through each of the 24 polar faces. This makes $B_{//} = 39{,}120$ in the armature core, and 57,000 in the magnet core. To produce this magnetization an exciting current of about 8·7 amperes is required in the field-magnet coils, the total resistance of which is about 11·2 ohms (warm). Hence the power wasted in the field-magnet is about 850 watts, or 2·83 per cent. of total output.

In Plate XXII. are given drawings of another Kapp alternator, built at the Oerlikon Works. This is an 80 HP. machine, running at 600 revolutions per minute, yielding 30 amperes at 2000 (virtual) volts, and weighing 3½ tons. Upon the same bed-plate is mounted an exciter. The field-magnet consists of two crowns, of 14 cylindrical wrought-iron magnets each, with rectangular pole-pieces. In each field-coil there are 186 turns, with total resistance 1·76 ohm, taking 21 amperes to excite fully. The ring has upon it 14 coils of treble cotton-covered wire, 0·120 inch in diameter, 80 turns each in two layers: total resistance 1·8 ohm.

For the Metropolitan Supply Company Mr. Kapp has designed some larger machines, giving 60 amperes at 2000 volts, at 600 revolutions per minute. The following are particulars of these machines:—Number of poles, 20. Frequency = 100 ~. Armature: foundation-ring, 42 inches diameter; core, 2¾ inches wide by 9 inches deep; winding 20 coils each 40 turns of copper tape, united in one series, $r_a = 0·926$; or if joined in two series, $r_a = 0·2317$, and output is then 120 amperes at 1000 volts. Field-magnet cores, 8½ inches long, 4½ inches diameter; pole-shoes, 8 inches by 3¼ inches; coils, 144 turns each; total resistance, 2·26 ohm; and carry exciting current 22 amperes to 25 amperes at full load.

Fig. 422.



Armature of Westinghouse Alternator.

Westinghouse (Stanley's) Alternator.—A drum armature is employed in the alternator[1] of the Westinghouse Company depicted in Fig. 422.

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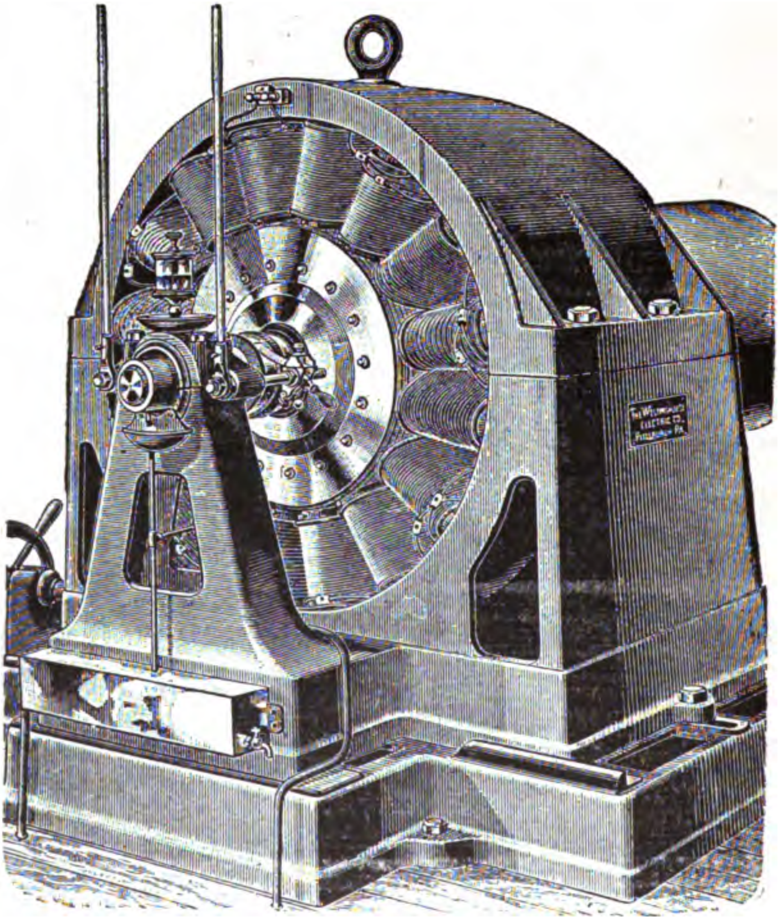
[1] For further information and tests see *Electrical World*, vol. xi., Sept. 3, 1887; vol. xv. 242, 1890; *Electrician*, xxv. 603 and 706, 1890; *Electrical Review*, xxv. 233, 1889; British Specifications of Patents, 9725, 9726, and 9727 of 1887; *La Lumière Electrique*, xxv. 643, 1887; xxvii. 8, 1888.

In the 150 kilowatt machine there are 16 radial poles pointing inwards and fixed externally to a common cylindrical cast-iron yoke. The armature core, which is 23 inches in diameter and 12 inches in length, is built up of thin iron disks, with holes perforated for ventilation. The winding consists of 16 coils, wound in flat hanks on special formers,

Fig. 423.



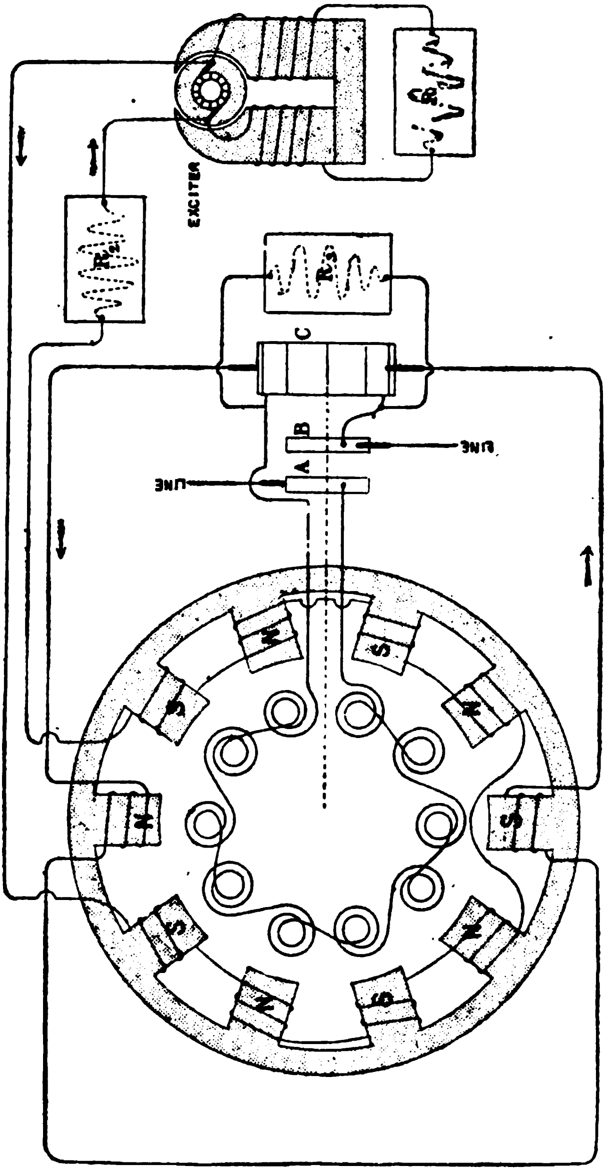
Westinghouse Alternator.

and then laid side by side upon the periphery of the core, not overlapping, and secured by well-insulated binding wires; the ends of the hanks being bent over and secured against the flanks of the drum. The grouping is in two series of eight coils each. The binding wires cover nearly the entire surface (see Fig. 422). This machine weighs three tons, and gives 145 amperes at 1100 volts at 1080 revolutions per minute. The journals are very long and are carried through spherical-seated bearings. To permit of repairs the upper half of the field-magnet can be lifted off. The exciting current is from 25 to 30 amperes at 100 volts. The number of alternations is 8640 per minute or 144 per second. In the most recent Westinghouse machines the armature coils are wound on toothed core-disks.

Elihu Thomson's Alternator.—This machine closely resembles the Westinghouse, but differs in important details. The armature coils, which are wound with square wire, cover a large amount of surface, and are not turned down in flaps over the ends of the drum. The field-magnets have from eight poles in small machines to 22 poles in the largest. In the small machines all the armature coils are united in one series as in Fig. 416; in the larger sizes they are in two series. Three types of these alternators are used. Some are separately excited: others are made self-exciting by the device of winding a few turns of wire in drum fashion around the core in the inter-spaces of the main coils, the end being brought out to a commutator on the shaft; others are called "composite," from the circumstance that the field-magnets are partly separately-excited and partly self-excited from the main current of the machine, which for this purpose is carried through a shunted commutator. It is this third class of machine which is depicted in Fig. 424. An exciter furnishes current to eight of the ten field-magnet poles, the excitation being controlled either by a variable resistance R_1 in the shunt circuit, or by R_2 in the exciting circuit. The other two field-coils are connected to brushes on a rectifying commutator C, shunted by the resistance R_3. The main current on its way to or from the contact-rings

A B must pass through this commutator or the shunt R_3.

FIG. 424.



ELIHU THOMSON'S ALTERNATOR: COMPOSITE METHOD OF EXCITATION.

Hence the excitation will be of two parts, an initial and constant part, and a variable part depending on and proportional to the main output of current. Hence this arrangement has the same virtues as the compound-winding of direct-current dynamos. The resistance R_3 which is of German silver attached to the frame of the machine, permits the amount of compensating excitation to be varied in different machines, so that the same size of machine can be used to compensate for the fall of potential over various lengths of line. This type of alternator is made in three sizes, giving respectively 35, 70, and 140 amperes at 1000 volts, at speeds from 1500 to 680 revolutions per minute.[1]

Prof. Elihu Thomson has devised another form of alternator, described on p. 686.

Blakey-Emmott Alternator.—This machine, depicted on Plate IX. and Plate XXIII., is of the same general type as the preceding; but whereas the windings of the two preceding sorts are lap-windings, that of the present machine is a wave-winding resembling Fig. 203, p. 314.

The armature core is built up of very thin charcoal iron disks mounted on a gun-metal spider keyed to the driving shaft. The winding consists of bands of copper wires, the breadth of the bands being equal to the width of the poles. These bands are laid in a sinuous form upon the surface of the armature, the bends being laid upon the end plates. The final ends are carried to substantial rings of copper serving as collectors. Carbon block brushes are used and are found very satisfactory. The bearings are self-centering. The sketch in Plate XXIII. represents the 15A size, which gives an output of 7·5 amperes at 2000 volts, or 15,000 watts at a speed of 1200 revolutions per minute. The number of poles is ten, and the frequency therefore 100 complete periods per second. The diameter of the armature core is 18 inches, and the length 8½ inches. The total number of active conductors in the armature is 1140, the weight of copper being 13·3 lb. The resistance is 4·48 ohms; and, when run on open circuit with full excitation, the volts generated are 2050. The weight of copper on the field-magnets is 150 lbs.

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[1] See *Electrical World*, xiii. 19, 1889; xiv. 197, 1889; and *Electrician*, xxvi. 133, 1890.

The curve of induction of this machine is given on p. 619. The armature can be readily examined in position by removing the top half of the field-magnets. These machines are made by Messrs. Blakey, Emmott & Co., of Halifax, in seven sizes, with outputs varying from 12,000 to 120,000 watts.

Phœnix Alternator.—This machine is constructed by Messrs. Paterson and Cooper, from the designs of Mr. Esson;[1] and has a general resemblance to those described, being multipolar with twelve poles. The magnet cores are of wrought-iron made narrow to receive the coils, and widening into a polar face nearly of double area. They are carried on a cast-iron yoke ring; and the width of the pole-faces is half the pitch. Had the cores been of equal width all the way along they might nearly as well have been of cast iron; but with wrought-iron of high permeability, the saving in copper more than pays for the cost of tooling. The armature is built up of core rings with internal and external diameters in the ratio of about 7 to 5, over which are laid six flat coils each equal in breadth to three times the width of the magnet cores, and laid on the periphery with spaces equal to the width of the core between them.

Hopkinson Alternator.—This machine has multipolar magnets, with a width of pole-face exceeding three-fourths of the pitch. The armature wires are not laid on the outside of a drum, but are coiled upon short polar projections of laminated iron. The machine shown runs at 800 revolutions per minute, giving 30 amperes at 1000 volts. The armature resistance is 0·55 ohm, and that of the magnet coils 2 ohms. The exciting current is 21 amperes. An electrical efficiency of 95 per cent. is claimed for the machine. Its exciter, a small "Manchester" dynamo, is mounted on a bracket to run on the same shaft. These machines (Fig. 425) are built by Messrs. Mather and Platt.

Ganz-Zipernowsky Alternators.—Various forms have been built[2] by Ganz & Co., of Buda-Pesth, chiefly from the designs of M. Zipernowsky. The general principle of these machines has already been described on p. 644; but some have been otherwise constructed. A very large machine was shown at Vienna, by Messrs. Ganz, in 1883. It was capable of furnishing light for 1200 Swan lamps (20 candle-power each). The thirty-six bobbins of the field-magnet were set concentrically on an iron frame, and rotated within an outer circle of thirty-six armature bobbins. The field-magnet coils

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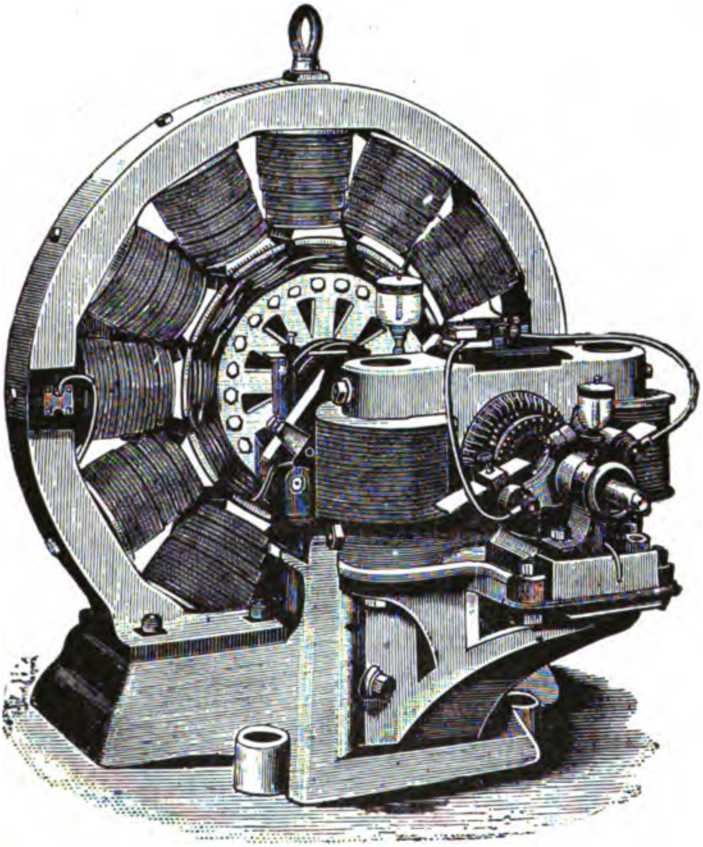
[1] *Journal Institution Electrical Engineers*, xx. 289, 1891.

[2] See *Centralblatt für Elektrotechnik*, xii. 554, 1889; also *Electrical Review*, xv. 70, 1884; xvii. 115, 1885; *Electrician*, xxv. 258, 1890; *Elec-*

Fig. 425.



Hopkinson Alternator.

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trical World, xiii. 297, 1889; xvi. 73, 1890; *La Lumière Electrique*, xxxi. 121; and xxxii. 159 and 582, 1889.

were, in fact, the fly-wheel of the high-pressure compound engine which drove the dynamo and its exciter. The diameter of the rotating part was 2½ metres. A salient feature of this machine was the fact that any one of the coils, either of armature or field-magnets, could be removed from the side of the machine in case such were needed. The whole fly-wheel could, in this way, be taken down by one man in a few minutes. The armature coils were attached flat against the inner periphery of a large ring of iron wire ; there being no cores protruding through the armature coils. At Frankfort, in 1891, a large Ganz alternator was shown by the Helios Co.,[1] of a capacity of 400 kilowatts, giving 200 amperes at 2000 volts at 125 revolutions per minute. The armature consisted of 40 T-shaped punchings, like Fig. 410, surrounded with coils each working at 100 volts, the whole being coupled up in two series of 20 each. The rotating field-magnet is 299·2 centimetres in diameter, and 38 centimetres wide. The electrical efficiency is given at 95·6, and the nett efficiency at 91·5 per cent. Four very fine examples of the Ganz alternator exist in the central station of Rome,[2] each being of 320 kilowatts capacity, driven direct at 125 revolutions per minute by separate compound engines of 500 HP. each. They have rotating field-magnets with 40 radiating poles of solid iron, the diameter being over 9 feet. The interior diameter of the armature ring frame is about 9½ feet, the core being built up of sheet iron and paper as described. There are 40 coils, each generating 50 volts, all united in series, and capable of carrying 200 amperes, the wire being 6 mm. in diameter. The bobbins of the field-magnet coils are wound on rectangular split-zinc formers about 15 inches high and 20 inches wide, the windings being more numerous toward the outer end. The armature windings, 30 in each coil, are contained on vulcanized fibre frames 19 inches long, 10 inches wide, and 2 inches deep, and are clamped in place by skeleton bronze frames.

Siemens Alternators.—Messrs. Siemens and Halske were early in the field in 1878 with alternators designed by von

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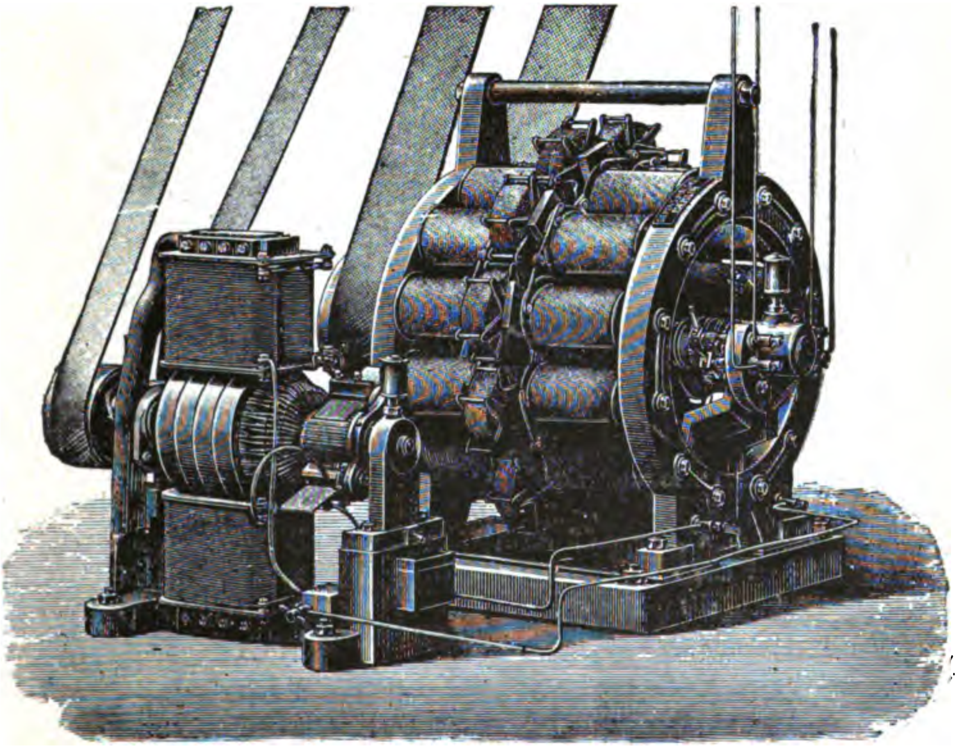
[1] See description by Mr. Esson, and cut, *Electrical Review*, xxix. 503, 1891.

[2] See description by Prof. Flemming in the *Electrician*, xxv. 317, 1890.

Hefner Alteneck; having a disk armature (see Fig. 412), in which the coils are wound usually without iron, upon wooden cores. Copper ribbons insulated from one another by strips of vulcanized fibre are used for the coils; the connexions being made by soldering the strips with silver solder. In some forms of the machine, the individual coils are enclosed between perforated disks of thin German silver. When currents of great strength are required, but not of great electromotive-force, the coils are coupled up in parallel instead of being united in series. In Fig. 426 a small continuous-current machine of vertical pattern, such as was described on p. 193, is shown in action as an exciting machine

Fig. 426.

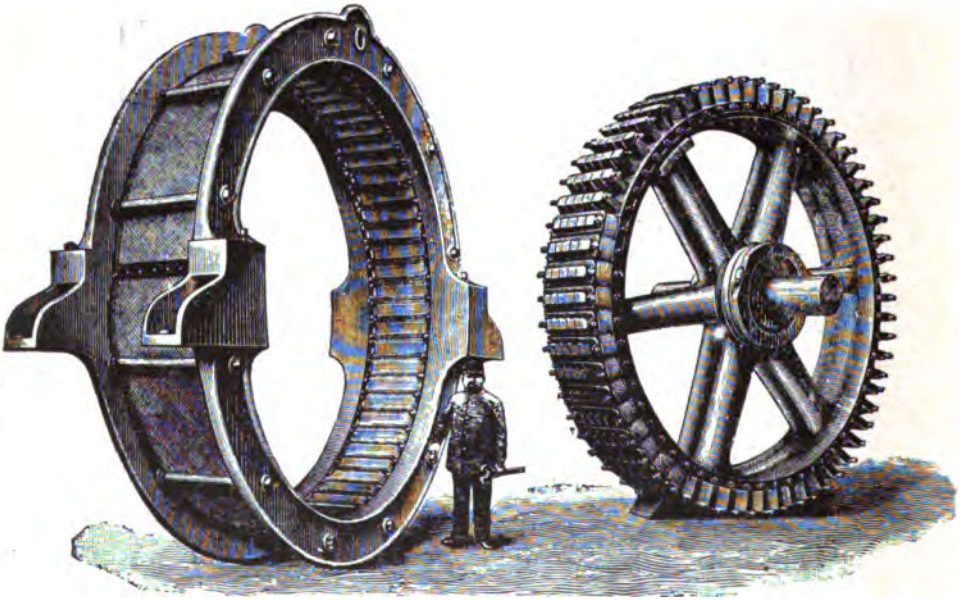


Siemens Alternator, with its Exciter.

to furnish the magnetizing currents to the stationary field-magnets of the alternator.

More recently Messrs. Siemens and Halske have returned to a pattern more nearly resembling Lontin's design, with a multipolar rotating field-magnet and fixed external armature. The large 330 kilowatt machine shown at Frankfort in 1891 is depicted in Fig. 427. The field-magnet consists of 60 bobbins with laminated cores built upon the rim of a fly-wheel, 3·7 metres in diameter over all; whilst the armature ring is 4·6 metres (14 ft. 9 in.) in external diameter. When running at 100 revolutions per minute, it yields 165 amperes at 2000 volts. The construction of the armature is as follows :—A laminated ring of 60 segments, each built up of straight iron plates stamped with end-projections, is held together firmly in a cast-iron frame. Each segment before being put in place is wound with 20 turns of a conductor made of stranded copper

Fig. 427.



Siemens and Halske Alternator.

wire compressed to a square section, each wire in the strand being lightly insulated with a coat of enamel. The ring thus formed is 4·6 metres in diameter, and 50 centimetres in width parallel to the axis; the end projections of the core-plates constituting 60 internal teeth. It is therefore simply a laminated Pacinotti ring with sections coiled alternately right and left-handedly. Any one of the sections can be removed singly for repair. The laminated magnet-cores carry 56 windings each, and receive a current of 56 amperes at 70 volts for excitation.

Gordon's Alternator.—Gordon's alternator was described and figured in the earlier editions of this book. It has twice as many coils in the fixed armatures as in the rotating magnets, there being 32 on each side of the rotating disk, or, in all, 64 moving coils; while there are 64 on each of the fixed circles, or 128 stationary coils in all. The latter are of an elongated shape, wound upon a bit of iron boiler-plate, bent up to an acute **V** form, with cheeks of perforated German silver as flanges.[1] The result of thus arranging the coils in two sets is that there are two distinct currents differing in phase by a quarter period. The armature parts of the machines used at Paddington have lately been reconstructed and laminated more thoroughly, to obviate the waste by eddy-currents, which was serious in the machines as first designed.

Elwell-Parker Alternator.—This machine, built by the Electric Construction Corporation, Wolverhampton, is shown in Plate XXIV. The field-magnets, which are internal and revolve, present a set of radiating poles, built upon a foundation ring of mild steel, into which the magnet-cores of soft wrought iron are securely bolted by **T**-shaped pieces, the head of each, which forms a pole-piece, grooved on its surface, and the shank of which passes through the core and foundation ring. The armature-core consists of an external asssemblage of segmental core-rings bolted between two end frames of cast iron. The armature coils, which are separately wound of copper tape on wooden cores, are secured by wooden clamps and iron bolts against the inner periphery of the core-rings. The external breadth of each armature coil is equal to the pitch, and the internal breadth is slightly less than the width of the pole-face.

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[1] For further details of the Gordon dynamo, see Mr. Gordon's *Practical Treatise on Electric Lighting* (1884), p. 162.

The following are particulars of two recent Elwell-Parker alternators of 30 and 50 kilowatts respectively:—

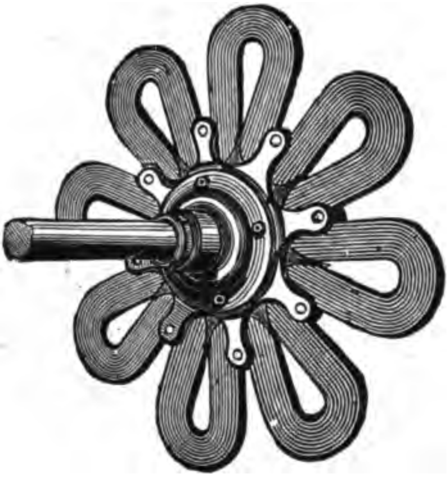
Output (watts)	30000	50000
Amperes	30	25
Volts	1000	2000
Frequency (periods per second)	60	83·3
Revolutions per minute	600	500
Number of poles	12	20
Diameter of F.M. circle	36″	45 5/16″
Length of magnet cores	6¾″	8⅝″
Section of magnet core:—Width	3″	2″
Breadth	6″	10″
Pole-faces:—Width	4½″	3½″
Breadth	6″	10″
Turns on each F.M. pole	267	344
Exciting current	16 to 18	11·6 to 12·3
Resistance of magnet coils (ohms)	3·26	9·5
Clearance from poles to coils of armature	⅛″	⅛″
Total clearance poles to core-rings	¼″	15/32″
Armature core, internal diameter	37″	46¼″
,, ,, external ,,	45″	56¼″
,, ,, external breadth	6¼″	10¼″
Armature coils, number of	12	20
Aperture in coil, length of	8″	12⅝″
,, ,, breadth of	4½″	3½″
External breadth of coil	9⅝″	7 3/16″
Turns in each coil	34	28
Width of copper ribbon	0·25″	0·25″
Thickness of copper ribbon	3·060″	0·049″
Total weight (lbs.) of copper on armature	60	115

Plate XXV. depicts the Elwell-Parker alternators as used in the central station at Manchester Square, London, each coupled direct to a triple-expansion high-speed Willans engine.

Ferranti's Alternators.—This machine, as brought out in 1882, was based on the joint but independent proposal of Sir W. Thomson and Mr. S. Z. de Ferranti to substitute wave-windings for coils.

Sir W. Thomson proposed originally that the armature should consist of copper strips wound in a star fashion between projecting teeth on a wooden wheel. He also proposed to use as field-magnets a form of electromagnet in which the wires that bring the exciting current pass up and down, in a zigzag form, between iron blocks projecting from an iron frame. In the machine as constructed at that date,[1] the field-

FIG. 428.



FERRANTI ARMATURE (1882).

FIG. 429.

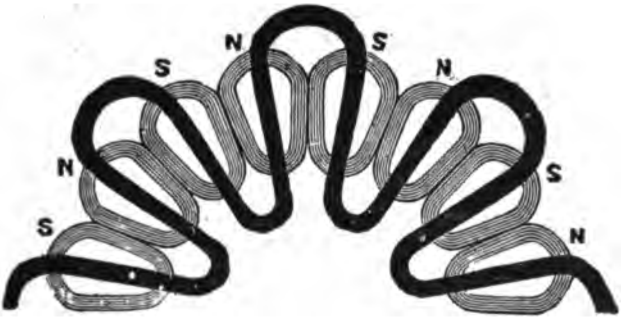


DIAGRAM OF (OLD) FERRANTI ALTERNATOR.

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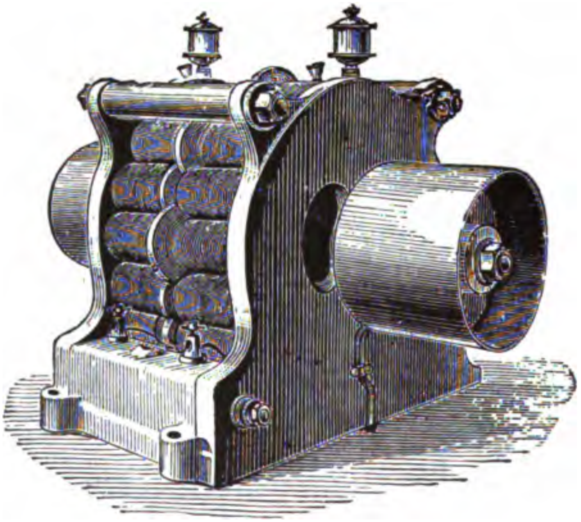
[1] See Specification of Patent, No. 3702 of 1883; and, for later details, No. 702 of 1887.

magnet consisted of two crowns of alternate poles, precisely as in the alternators of Wilde & Siemens; and the armature consisted of strip copper bent into a wavy star form. There were eight loops in the zigzag (as shown in Fig. 429, which depicts half only of the arrangement), and on each side were sixteen magnet poles; so that the moving parts were twice the angular breadth of the fixed parts. The copper strip was wound round on itself (with insulation between) in many layers; the limbs of the star being held in place by insulated bolts passing through star-shaped face-plates of brass. The advantage of the armature of zigzag copper was supposed to lie in its strength and simplicity of construction.

FIG. 430.

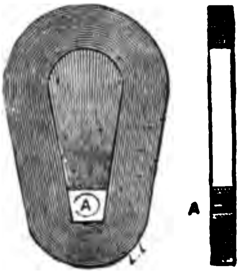


FERRANTI-THOMSON DYNAMO.

The framework of the field-magnet was cast in two halves, which were held together by bolts.

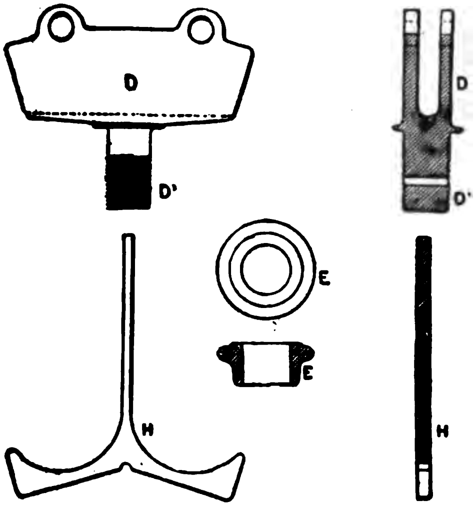
In the later alternators of Ferranti the zigzag mode of winding has been entirely abandoned, and the coils are wound separately and then assembled into a disk. The mode of construction is explained by the figures which follow, and by those on Plate XXVI. Each coil is wound upon a rigid core. The cores are constructed of brass strips spreading fan-wise, with asbestos between, brazed solidly together at one end, and to a brass piece which is drilled with an aperture A (Fig. 431). The winding, the inner end of which is soldered to the brass piece, is of ribbon copper slightly corrugated to secure greater rigidity, wound with a tape of thin vulcanized fibre between. The coils are mounted in twos in brass coil-holders, depicted at D, Fig. 432, into which, with interposed layers of mica and fibre, they are secured by bolts which pass through their eyes. The two coils in each holder are separated mechanically and electrically by interposing a piece of fibre of the form shown

FIG. 431.



SINGLE COIL OF FERRANTI ARMATURE.

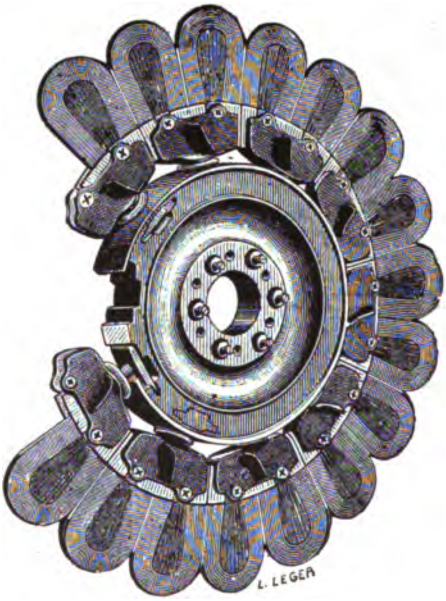
FIG. 432.



DETAILS OF FERRANTI ARMATURE.

at H; but the holder constitutes a metallic connection from the eye A of the one to the eye A of the other. Consequently, a current circulating from outside to inside of one coil must circulate from inside to outside of the other. The outside end of each coil is joined to the outside of the nearest coil in the next holder. The holders must of course be insulated, and yet held mechanically and firmly. For this purpose they are provided with a tail-piece D′, of circular section, which passes through a porcelain bush E, and is threaded to receive a metal foot which is further secured by a pin passing through D′. The tail-piece, protected by its porcelain bush, passes through the rim of a strong foundation ring, having apertures into which the metal feet are inserted, but which are much wider than them. The gap between them is then filled up by pouring in a molten compound of sulphur and powdered glass, which secures and insulates them. On the side of each coil-holder projects a small oblique wing, to promote ventilation. In all the larger machines the coils are connected up, as shown in

FIG. 433.

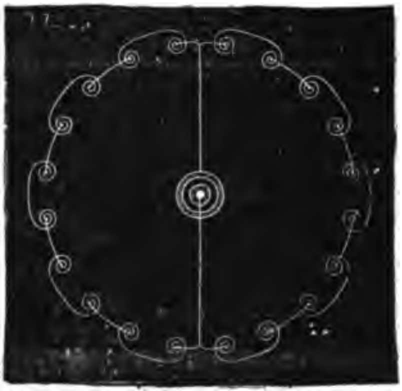


FERRANTI ARMATURE, SHOWING MODE OF MOUNTING COILS AND COIL-HOLDERS.

Fig. 433, in two series, which are joined together in parallel. This grouping is effected by placing all the coils in one half circumference right-handedly, and in the other left-handedly.

Two copper rods pass inwards from the tail-pieces of two of the coil-holders at opposite ends of a diameter, and are led to the collectors.

FIG. 434.

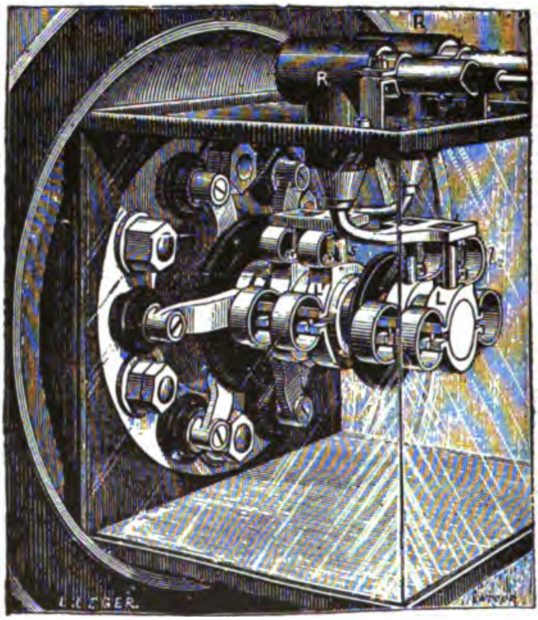


CONNEXIONS OF FERRANTI ARMATURE.

The collecting arrangements are separately shown in Fig. 435, and are mounted on the end of the shaft. One connexion from the armature coils communicates with a structure consisting of three arms at 120° apart. These passing out through ebonite bushes unite to a copper cylinder, which passes through a large ebonite bobbin provided with deep flanges at back and front. Upon the front end of this cylinder two collectors press, each collector consisting of two half-rings L of copper united by C-shaped springs. These two collectors are united by a curved connector to the insulated junction-piece R going to the circuit. The other connexion from the armature coils is united by three other arms to a copper mantle outside the ebonite bobbin, and on this mantle press two other collectors L′, similar to, but slightly larger than the former pair. These communicate with the other pole of the circuit.

In Plate XXVI. are depicted two forms of Ferranti's alternators. Fig. 1 relates to a 300 horse-power machine, and gives a view of half the armature and half the field-magnet. Here it is seen how the copper connector D^2 passes from the coil-holder D to m_1, a bolt uniting it to one of the three arms of the collecting apparatus. The cut also shows how the field-magnet is built in two separate halves, each of which can be

FIG. 435.



COLLECTORS OF FERRANTI'S ALTERNATOR.

racked laterally aside by a lever N and rack M to expose the armature for cleaning or repairs. The speed of this machine is 350 revolutions per minute, and the diameter of the armature 5 feet 6 inches.

Figs. 2 and 3 of Plate XXVI. represent on a scale of $\frac{1}{50}$ the 1250 horse-power alternator as used at the Deptford lighting-station. These machines, capable of giving 100 amperes at 10,000 volts, when running at 120 revolutions per minute, are driven by rope-gearing from engines of marine type. The pulley, which has grooves for 27 ropes, is nearly

10 feet in diameter, and over 10 feet long. It is built in two parts N and N_1, united by bolts at *a*, and is keyed to the middle of the shaft between two bearings γ mounted on pedestals which curve inwards at both ends. The journals are of unusual length, and the bearings swivel upon spherical seats. End play is prevented by collars at the outer ends of the shaft. The exact position of the pulley upon the shaft can be adjusted by a central screw collar *c*, turned by a handle U. This adjustment is rendered necessary because the armature is mounted upon the end rim F of the pulley itself, overhanging the bearing; and, as the clearance between the armature-coils and the magnet pole-faces is very small, any wearing of the bearings might cause the armature coils to come dangerously close to the pole-faces. The coil-holders and porcelain bushes are shown at D and E. The magnet-poles are held in a large external cast-iron frame. There are 48 poles in each crown, of alternate polarity. The faces are covered with caps of thin ebonite to protect against spark discharges from the coils. The armature coils, also 48 in number, are each capable of generating about 420 volts, and will carry a current of 50 to 55 amperes without undue heating. The mean diameter of the armature is 15 feet, and its thickness at the working part is only ¾ inch. The peripheral speed is therefore 5850 feet per minute. Owing to the mode of driving the armature, the insulated copper connexions must pass through the bearing, and are therefore carried along in a channel through the shaft. The most elaborate precautions are taken against the possibility of a stoppage arising from over-heating of the bearings. There is a double circulation of water and of oil. On the end of the shaft opposite to the collecting apparatus an eccentric works an oil-pump *p*, which pumps oil through a filter out of the reservoir R under the platform, and distributes it under pressure to the oil-ways *a* in the bearings, whence it returns to the reservoir.

In Plate XXVII., Figs. 1 and 2, are given drawings of the still larger alternator, nearly completed but not yet erected, at Deptford. This machine will furnish 750 amperes at 10,000 volts, furnishing light for 200,000 glow-lamps, and requiring 10,000 horse-power when running at 60 revolutions per minute. The mean diameter of the armature is 45 feet (nearly 15 metres), with a peripheral speed of nearly 8000 feet per minute. The coils, of which there are 48 pairs, are constructed and connected as in the machines previously described, but are carried upon the rim of a large fly-wheel, the rim of which weighs nearly 200 tons. The weight of the completed armature is about 225 tons. The two crowns of field-magnets weigh together with their frames about 450 tons. The armature-wheel is carried upon the middle of a long crank-shaft, having a crank outside the bearings at each end. Right and left stand two compound marine engines, each of 5000 horse-power, which stand about 60 feet high from the ground, and about 80 feet high from the bottom of the magnet-frame, which is sunk below the level of the ground in order to lower the level of the shaft. The collecting arrangements, though not placed at the end of the shaft, are very similar to those of the smaller machines.

Parsons Alternator.[1]—This is a bipolar machine, running at the extraordinary speed of 6000 or even 8500 revolutions per minute; the armature being a plain drum. It is coupled direct to a special high-speed steam turbine by the same inventor.

Mordey's Alternator.—This striking form of machine, first brought out in 1888, is constructed by the Brush Electric Engineering Company, of London. It is depicted in Figs. 436 and 437 and also in Plate XXI. It differs in several essential features from the antecedent forms. Though, as before, there are two crowns of poles between which the armature lies, all the poles on one side are of one kind, north poles, and all those on the other side are south poles. Hence there is no reversal of the magnetic field through the armature coils; the number of magnetic lines through any coil simply varying from zero to maximum and back. As a result of this arrangement, there is a great simplification of the means needed to magnetize the field-magnets. It is no longer necessary to wind a separate magnetizing coil on each protruding pole. One single coil surrounding a central cylinder of iron suffices to magnetize the whole of the poles. There is indeed only one magnetic circuit, branching into separate branches. The construction of the field-magnet, of which a section is given in Plate XXI., and which is separately shown in Fig. 437, is as follows:—

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[1] See *Electrician*, xx. 103, 1887; and *Proc. Inst. Civil Engineers*, xcvii., Feb. 1889.

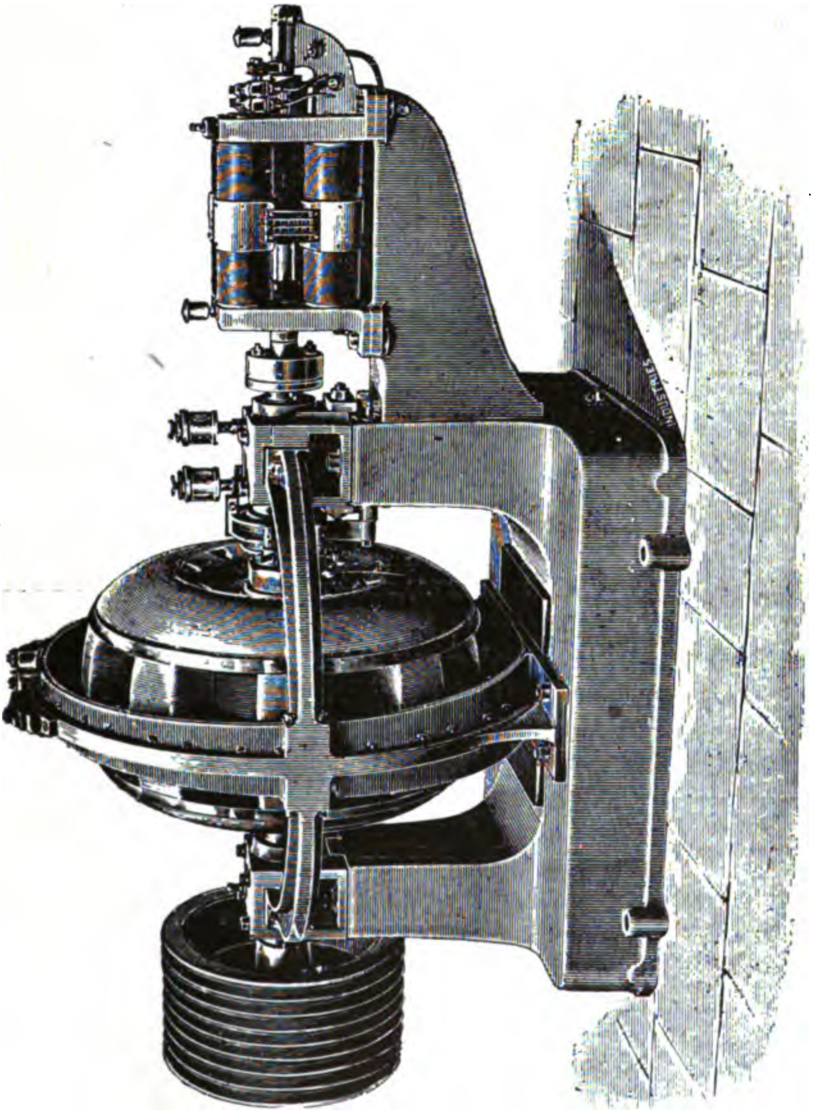
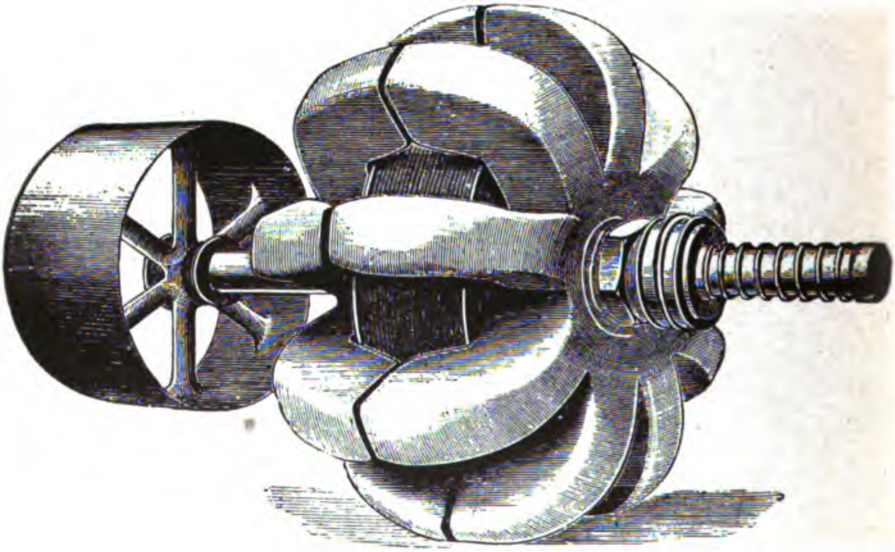


Fig. 436.

Mordey Alternator (75 Kilowatt) with its Exciter.

A short cylinder of wrought iron, through which the shaft passes, forms the core, and is surrounded by the exciting coil. Against the ends of this core are firmly screwed up the two end castings, each of which is furnished with a number of curved horns (nine in small machines, twelve in larger ones), projecting to within about 17 millimetres, the narrow polar gap being only just wide enough to admit the armature. The entire field-magnet revolves on the shaft, the exciting coil being supplied with current from a separate machine of small size by means of the two contact rings on the shaft on the right in Fig. 437. There is no need for the exciting coil to revolve; but for mechanical reasons it was deemed preferable to wind it actually upon the field-magnet core. The armature (Fig. 438), which stands still, consists, in the smaller machines, of 18 coils of narrow ribbon copper 11 millimeters wide, separated by strips of very thin fibre wound on porcelain cores. The separate coils are clamped at the broad end, by means of German-silver coil-holders lined with mica and

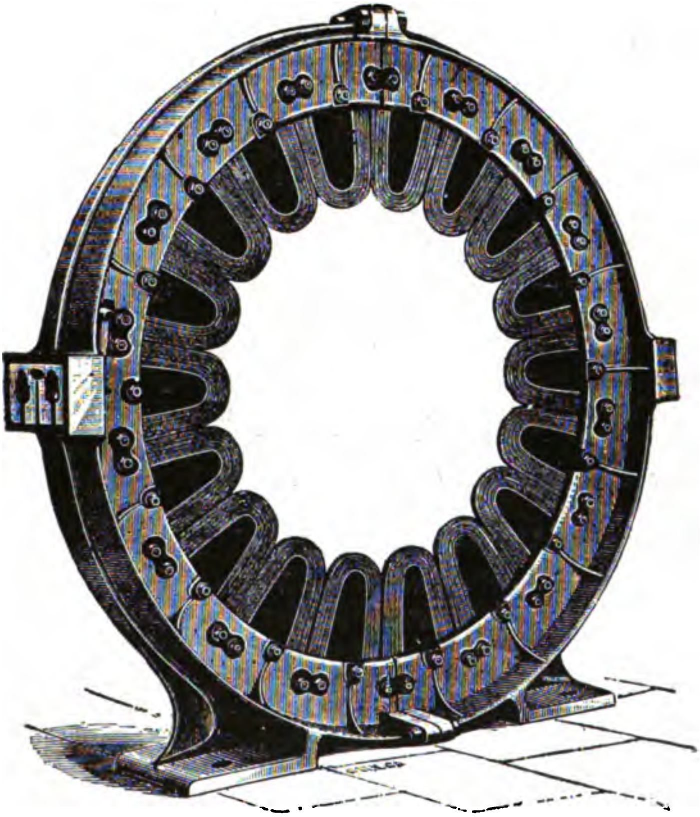
Fig. 437.



FIELD-MAGNET OF MORDEY'S ALTERNATOR.

fibre and embedded in ebonite, to a light but firm frame of gun-metal, the ends of the conductors of each coil being brought out through porcelain insulators and suitably connected together. All the metal clampings are outside the magnetic field, and they are so arranged that any one coil can be removed in a few moments without dismounting any other part of the machine. Each of the coils is provided with a screw device for thrusting it towards the centre, so that all the coils are wedged tightly together. As the armature is stationary there are no centrifugal forces to be con-

Fig. 488.



Armature of Mordey's Alternator.

sidered, and the coils have to be supported only with a view of resisting the tangential drag of the field. This renders the insulation of the armature coils a very simple matter, and is of great importance in working at high volts. The revolving field-magnet forms an excellent fly-wheel, effectually neutralizing any pulsations due to irregularities in the stroke of the engine, and as there are no parts liable to fly out, a high speed of driving presents none of the difficulties that arise with many other types of machine. In Fig. 436, which gives a view of the complete machine, the field-magnets are almost hidden by the external webs which cover the spaces between the projecting poles to prevent too great a disturbance of the air by the rotating pole-pieces. The shaft, as shown in Fig. 437, is provided at one end with a thrust-bearing resembling that of a marine propeller, and the bearing blocks are made adjustable longitudinally, so that the field-magnet may be placed exactly symmetrically with respect to the armature. In the latest machines end-play is prevented by shoulders on the journals, this form being less liable to heat. The exciter is a small four-pole Victoria machine (p. 498), weighing but $\frac{1}{40}$ of the weight of the alternator: the excitation taking 1 HP. The electromotive-force in a 20 kilowatt machine is 1 volt per 8½ inches of conductor in this machine. The very low resistance of the armature, and almost complete absence of armature reactions, makes the machine almost self-regulating. One advantage in this type of machine is the little labour required in winding its coils; and the simplicity of the tooling and fitting of the iron portions is a great gain.

The following is a description of the 75 kilowatt (or 100 HP.) alternator depicted in Plate XXI. Output (as usually wound) 37·5 amperes at 2000 volts, when running at 500 revolutions per minute. As there are 12 poles, the number of periods is 6000 per minute or 100 per second. The armature consists of 24 coils, usually wound so as to be all united in series: each coil working at 83·3 volts and having a resistance of 0·051 ohm. The total resistance of the armature is 1·22 ohm; hence at full load the lost volts are $37{\cdot}5 \times 1{\cdot}22 =$

55·75, and the watts lost by internal heating 1715. The armature coils are wound with copper strip 0·375 inch wide and 0·030 inch thick, the turns being separated by an insulating tape so thin as to be transparent. The polar gap is 0·75 inch across. The amperage at full load is no less than 3300 amperes per square inch. This figure, which in many types of machine would involve unsafe heating, is not high enough to do more than produce a gentle rise of temperature owing to the excellent conditions of ventilation. So it comes about that in this machine the limit of current-density is not fixed by risk of overheating, but by considerations as to the efficiency and the slope of the characteristic. For the other losses in the armature have been reduced to a negligibly small amount by attention to details. Loss by hysteresis there is none, owing to absence of any armature core. The eddy currents in the tape are trifling, it being so thin and needing no further lamination. Further, the coil-holders do not penetrate into the polar gap, but merely pass across the fringe of the field. They are moreover of German-silver, the high specific resistance of which alloy reduces the losses by eddy currents to $\frac{1}{16}$th or $\frac{1}{20}$th of what they would be if brass were used. That the waste is almost entirely confined to the i^2r loss is afforded by the fact that the machine when driven on open circuit, but excited to give its full voltage, only absorbs 3 HP., the armature keeping quite cool. This is a very important point in all machines intended for central station use, as the wasted power forms a very much higher percentage of the total power when machines are running with light loads, than when they are fully loaded. And it by no means follows that a machine which shows a high efficiency at full load will show a high efficiency at low loads during the day-light hours. This is a point which Mr. Mordey early recognized and strove to meet in his designs. The field-magnet coils are usually wound to take a current of 17·6 amperes at 65 volts; or requiring 1150 watts, at full excitation. The electrical efficiency may be calculated as follows. Nett output 75,000 watts; armature loss 1715 watts; field-magnet loss 1150 watts; total power absorbed 77,865 watts;

electrical efficiency 96·32 per cent. The makers guarantee a commercial efficiency of 93 per cent. The closeness of agreement of the commercial efficiency with the electrical efficiency is a measure of the goodness of design; being a proof of absence of friction, hysteresis and parasitic currents. It is a curious point that in many machines these losses, though great at low loads, are not only proportionally but actually less at full load. But machines which show great losses at low loads are uneconomical for central station work.

The Brush Electric Engineering Company has just completed some large alternators of 250 kilowatt capacity, having a nett efficiency of over 95 per cent. These are provided with a special oil-pump, consisting of two toothed wheels about 1½ inches in diameter, geared to one another, and enclosed, which draw in the oil between the teeth and deliver it under the journals at a pressure of about 60 lbs. per sq. inch. There is a sight-drain for the oil, enabling the attendant to be sure that the lubrication is efficient. The following are particulars of a 250 kilowatt alternator :—

Field-magnet has 20 pairs of poles; revolving at 300 revolutions per minute gives 100 periods per second. Weight of revolving magnet and shaft 15 tons : total weight of machine 20 tons. Magnetization of poles, 7400 lines per square centimetres. Breadth of single armature coil, 7$\frac{1}{16}$ inch (— 9°); effective length of ditto 10⅛ inch; width of coil, ⅝ inch. Excitation on open circuit takes 2800 watts : at full load, 3650 watts, or less than 1¼ per cent. of output. Drop in volts at full load, if excitation is constant, 4¼ per cent; electrical efficiency (including excitation), 97 per cent.; guaranteed commercial efficiency, 93 per cent. The sliding connexions for the exciting current are made by two flexible strips of metal gauze, weighted at one end, which hang over the two contact-rings.

Some still larger machines of 500 kilowatts are being constructed from Mr. Mordey's designs.

Mr. Mordey has designed[1] a considerable number of alternative forms, all characterized by the combination of the two principles of simplicity of magnetic circuit and non-reversal polarity in the armature. Some designs for machines of kindred type have been patented by W. Main.[2]

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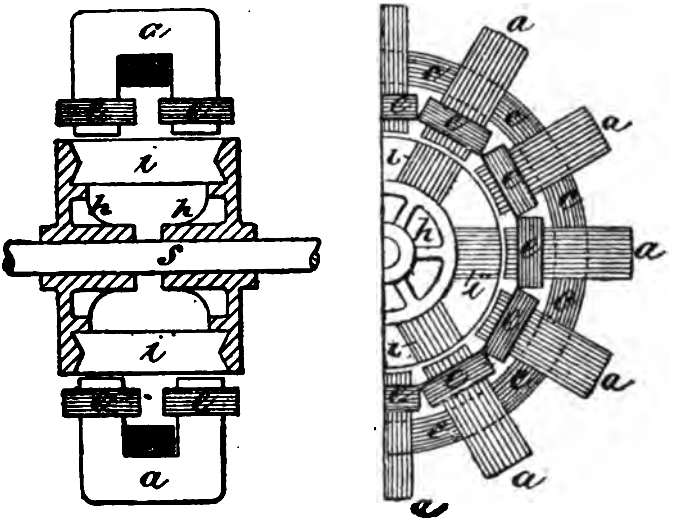
[1] Specification of Patent, 8262 of 1887.

[2] Specifications Nos. 15,858 and 16,032 of 1887. The device of employ-

INDUCTOR ALTERNATORS.

Mordey's Inductor Alternators.—An inductor alternator of Mordey's design is shown in Fig. 439. The armature coils *e* are placed upon the ends of U-shaped iron stampings *a*, arranged in sets around a single exciting coil *c*. A number of plates of laminated iron *i*, fixed upon a central wheel, are carried past the outer masses of iron, and reinforce their magnetic circuits in alternating succession.[1]

FIG. 439.



MORDEY'S INDUCTOR ALTERNATOR (First Type).

Although in this form only a single annular field winding is used, the armature winding consists of a considerable number of coils. In a later patent[2] the same designer has suggested several forms in which he employs only a single annular winding for the armature as well as for the field. Fig. 439*a* shows

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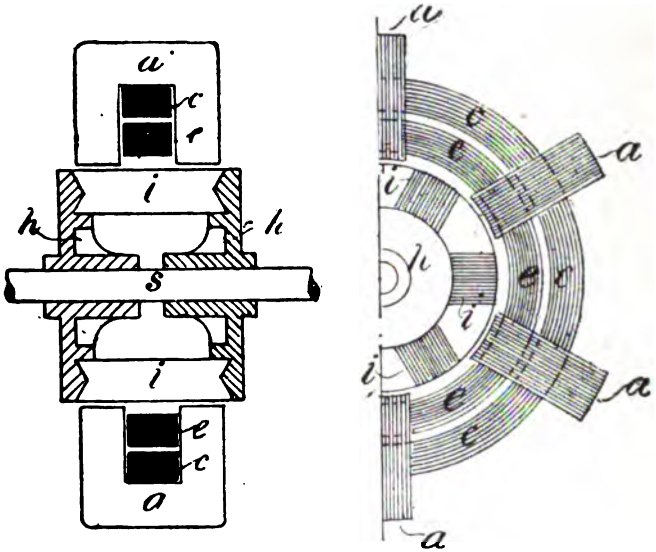
ing field-magnets with a greater number of pole-pieces than of exciting coils had been previously employed by Holmes (Specifications 2060 of 1868), and more recently by J. and E. Hopkinson.

[1] This principle suggested, by several early workers (see Historical Notes, p. 11), was revived by the author of this treatise in 1883, in a form which is described in his Specification of Patent, No. 1639 of 1883, and which led up to Mr. Kingdon's. Drawings of this latter machine are given in *Electrical Review* xxii. 178, 1888.

[2] No. 5162 of 1888.

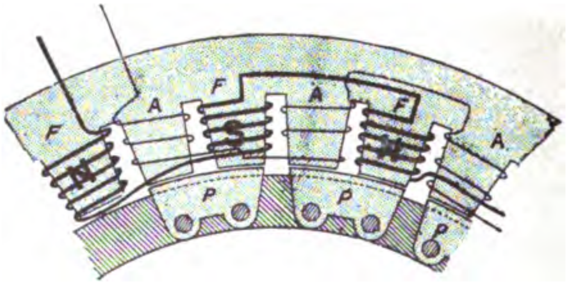
the application of this principle in an inductor alternator, in which *c* is the exciting coil and *e* is the armature winding. This machine may be looked upon as an apparatus for periodically varying the mutual induction between two circuits, in one of which there is a steady current.

FIG. 439A.



MORDEY'S INDUCTOR ALTERNATOR (Second Type).

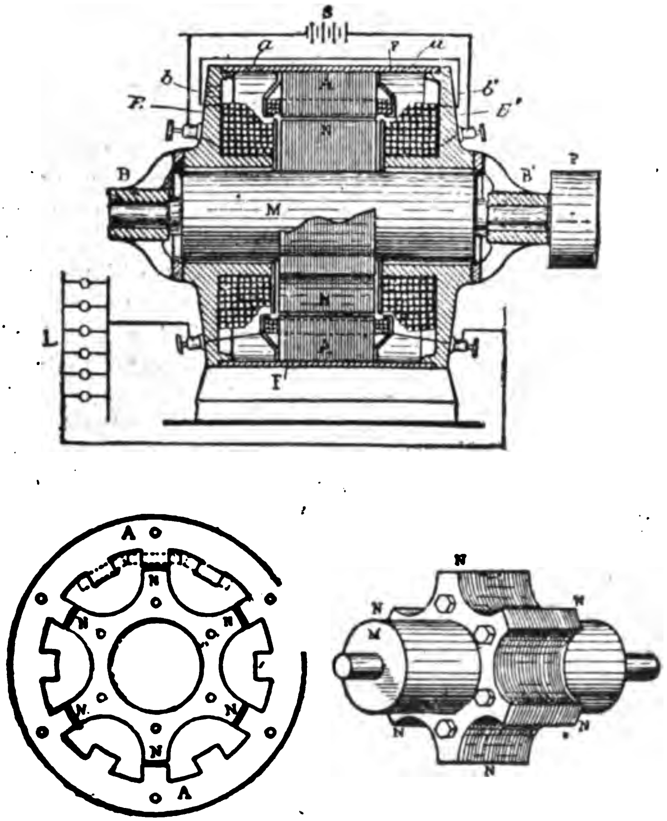
FIG. 440.



KINGDON'S INDUCTOR ALTERNATOR.

***Kingdon's** Inductor Alternator.*—The last-mentioned machine closely resembles an earlier and successful design of Mr. J. A. Kingdon. In this dynamo the principle of fixing both armature and field-magnets is applied in a different fashion. A ring having a large number of internally projecting poles is entirely built up of laminæ of soft iron. The alternate poles A are wound with coils to serve as armature parts, whilst those between them F are wound with other coils

FIG. 441.



ELIHU THOMSON'S INDUCTOR DYNAMO.

to act as the magnet part. Upon an internal wheel are borne masses of laminated iron P, which in rotating produce rapid periodic reversals in the magnetic polarity of the cores of the armature parts, and set up alternate currents in the coils that surround them.

In the 50-kilowatt machine there are 16 field-magnet or primary coils, and 16 armature or secondary coils. The inductor wheel carries 16 inductor blocks each, just long enough to span the width of two successive coils on the poles of the outer ring. Its diameter is 4 feet 5 inches, and breadth 12 inches; speed 350 revolutions per minute. Two of these alternators supply the central station at Woking. Another was shown at Frankfort by Messrs. Woodhouse and Rawson.

ELIHU THOMSON'S INDUCTOR ALTERNATOR.—In this machine also, the only rotating parts are of iron. On a central cylinder of iron, M (Fig. 441), are fixed a number of plates stamped out to the form shown at N. Outside this revolving part is an armature A built of toothed core disks, having coils on the inwardly projecting teeth, which are twice as numerous as the projections of the inductor part N. Some fixed coils placed on either side of N are separately excited so as to make N a north pole, and the end frames of the machine south poles. Hence the inductor becomes virtually a rotating field-magnet, having a set of poles of but one polarity, which completes their magnetic circuit through the armature coils in alternate succession. Some large central station alternators on this plan, having a capacity of 375 kilowatts, have lately been constructed. The inductors are carried on a wheel 6½ feet in diameter. There are thirty-six armature coils.

Kennedy's Alternators.—Numerous ingenious designs of kindred type have been produced by Mr. Rankine Kennedy.

CONSTANT-CURRENT ALTERNATORS.

A variety of alternators for supplying currents of an unvarying number of virtual amperes for the purpose of arc-lighting in series has been evolved in the United States; the principal forms being those of Stanley [1] and of Heisler.[2] The principle of these machines is to so construct the armature that it has great self-induction. This is accomplished in the Stanley constant-current alternator by using in the armature a fine wire of many turns wound deep in nicks in the core-disks.

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[1] *Electrical World*, xv. 45, and xvi. 339, 1890; also *The Electrician*, xxiv. 623, xxv. 145, and xxvi. 20, 1890.

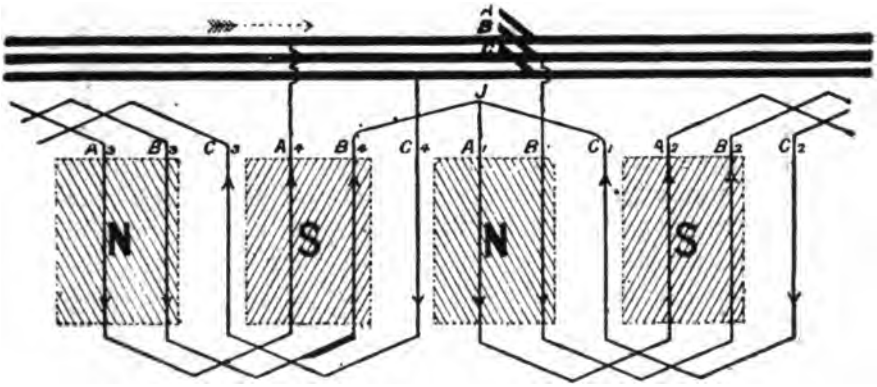
[2] *Electrical Review*, xxv. 207, 1889.

MULTIPHASE ALTERNATORS.

It has been pointed out on p. 642 that the separate circuits of the winding of Gramme's alternator would yield alternate currents which differ in phase from one another, and, therefore, must be used in different circuits. Quite recently alternators generating currents of different phases have come into vogue, not for lighting but for supplying power to motors of a special class (see p. 703), namely those requiring multiphase currents.

The principle of multiphase working consists in providing the armature of the alternator with coils grouped in sets of two, three, or more, which come successively into action in each period. Several ways of arranging such windings are further considered in Chapter XXIV, on Alternating Motors. For the present it will suffice to say that whether the armature be of ring, drum, pole, or disk type, it is always possible to arrange for multiple circuits by properly spacing the coils with respect to the field-poles, and the method is equally applicable to lap-windings and wave-windings. One example only is given here, of a three-phase winding. In Fig. 442 are shown three separate wave-windings A, B, and C, which are

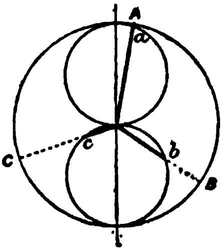
FIG. 442.



DEVELOPED DIAGRAM OF THREE-PHASE WINDING.

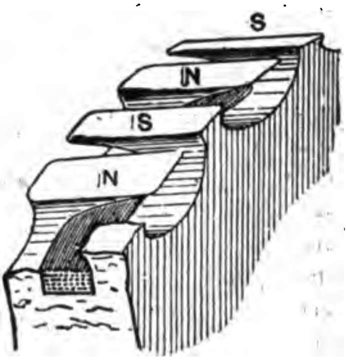
spaced out at equal distances from one another, the width between the separate active conductors being one-third of the pitch. At one point J these three windings form a common junction, whilst their other ends are supposed to be connected to three contact rings, to each of which there is a collecting brush. This figure should be compared with the ordinary alternator windings, Figs. 202 and 203, on p. 313. The winding shown would yield three currents differing in phase by 120°. The three-phase principle may be illustrated by a diagram such as Fig. 443 on the same plan as Fig. 396, p. 621. The three lines at 120° apart are supposed to rotate; and the lengths cut off by the two inner circles indicate the values of the varying electromotive-forces in the three circuits.

FIG. 443.



Brown's Three-phase Alternator.—This alternator, which was designed for supplying the currents in the famous transmission of power from Lauffen to Frankfort, in the autumn of 1891, was constructed at the Oerlikon works. Its aspect is shown in Plate XXVIII. The machine generates three currents each of 1400 amperes at a pressure of 50 volts, taking 300 HP. when running at 150 revolutions per minute. The armature, which is external, is stationary, whilst the field-magnet, which has 32 alternate poles, rotates within. The latter is shown separately in the second figure. The armature winding consists of 96 copper rods, each being 29 mm. in diameter, arranged in three sets of 32 each, connected as in Fig. 442. These rods, insulated within asbestos tubes, are buried in holes punched in the core-disks, (see p. 347), just within the inner periphery. The core-disks. which are stamped out in segments, are assembled in a strong cast-iron frame, which can be moved bodily along the bed-plate, exposing the field-magnet for cleaning. The field-magnet is of great solidity and simplicity, having but a single magnetic circuit. The exciting coil is wound on the periphery of a sort of pulley of cast iron, to which are bolted two steel rims, each of which has 16 projecting horns. These horns project inwardly, the N-poles between the S-poles over the exciting coil in the manner sketched in Fig. 444. This arrangement, which in general resembles Mordey's, reduces the cost of construction and of excitation to a minimum. In fact, on open circuit only 100 watts are spent on excitation—one twentieth of one per cent. of the output; and at full load, when the armature reaction is a maximum, it is still far less than one per cent. This excitation is furnished by a small Oerlikon dynamo. For convenience of use with a turbine, the field-magnet is over-hung. The exciting current is conveyed to the rotating part by means of flexible metallic cords running over insulated pulleys, in lieu of the usual contact-rings and brushes. At full speed and normal voltage, the loss by friction and hysteresis is 3600 watts, or under 1·7 per cent. of the maximum output. The loss by resistance of armature windings at full load is 3500 watts, making total loss under 4 per cent., and commercial efficiency 96 per cent. The heating is, in the total absence of eddy-currents, quite negligible. The weight is 4½ tons. Alternators of this type will run as motors, synchronously, but with the great advantage over ordinary two-phase alternators of being self-starting.

Fig. 444.



Sketch of Detail of Field-Magnet.

Coupling of Alternate-current Dynamos.—The chief principles governing the working of two or more alternate-current machines on the same circuit were experimentally discovered by Wilde, and described by him in a paper published in the *Philosophical Magazine* as far back as January 1869. In the midst of the labour devoted during succeeding years to the development of direct-current machines, Wilde's paper appears to have been quite forgotten, and it was not until

Dr. Hopkinson independently took up the question and treated it in his lecture on "Electric Lighting," before the Institution of Civil Engineers in 1883, that attention was recalled to the subject. Dr. Hopkinson's method of procedure differed essentially from Wilde's in that he first deduced the behaviour of certain alternate-current dynamos under given conditions from theoretical considerations, and afterwards, when opportunity occurred, practically tested and verified his theoretical conclusions. In the following remarks we shall chiefly follow the line of argument used by Dr. Hopkinson.

In order that two or more alternate-current machines may work usefully together, it is easily seen that the periodic time of the alternations of one machine must be exactly equal to or at least some very small multiple of the periodic time of the other. In practice only the first case has been carried out hitherto. Let us consider then the case of two exactly similar and equal machines, A and B, running at the same speed so that the periodic time of the alternations of electromotive-force is the same in each machine. If the phase[1] of these two machines happens to be exactly the same, and they are joined in series, then evidently the two electromotive-forces will be added together and the two machines will behave as one. But such a condition of affairs will be unstable; and if anything happens, such as a slip of one of the driving-belts, to alter slightly the exact agreement of phase, the mutual electrical action will *tend* to increase the difference of phase instead of counteracting it. In Fig. 445 let the abscissæ measured along O X represent time, and the vertical distances electromotive-force; then the curves A A A and B B B will represent the march of the alternations of electromotive-force in the two machines, the curve B B B, which lies to the right of A A A, being the one corresponding to the machine which lags behind the other in phase. The curve E E E, which is obtained by adding the ordinates of the other two curves, gives the resultant electromotive-force in the circuit at any instant. As shown on p. 627, the current will have the same periodic time as this last electromotive-force, but will lag behind it in phase. It may therefore be represented by the dotted curve I I I, in which the ordinates represent current instead of electromotive-force. Now the rate at which either machine is putting energy into the circuit at any instant is given by the product of the ordinate of I I at that instant by the ordinate of the electromotive-force curve for that machine at the same instant. Thus at the instant N the machine A is doing work at the rate N K × N G, and the machine B at the rate N A × N G. The meaning of the product being sometimes negative is that the machine is at that moment *absorbing* energy from the circuit. The *total work* done by either machine during a complete alternation of current is obtained by summing up for the whole alternation the above products, each multiplied by the small interval of time $d\,t$ during which it can be assumed to be constant. This is most readily summed analytically, but may be done graphi-

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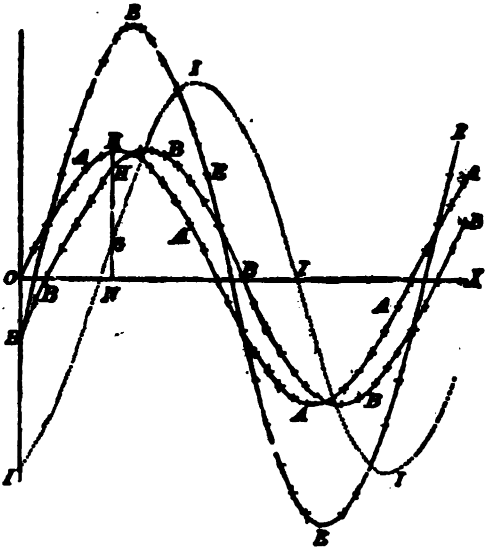
[1] By the phase being the same we mean that the maximum of positive electromotive-force occurs at *exactly the same instant* in each machine. In any other case the phases differ.

FIG. 445.



cally as follows. Plot a new set of curves, in which the abscissæ are the same as before, but the ordinates are the products of electromotive-force and current for each machine for each instant of time. The result will somewhat resemble

Fig. 446.

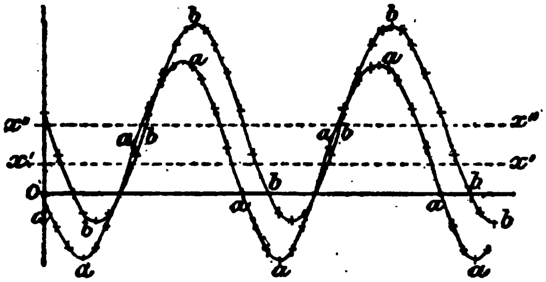


Fig. 447.

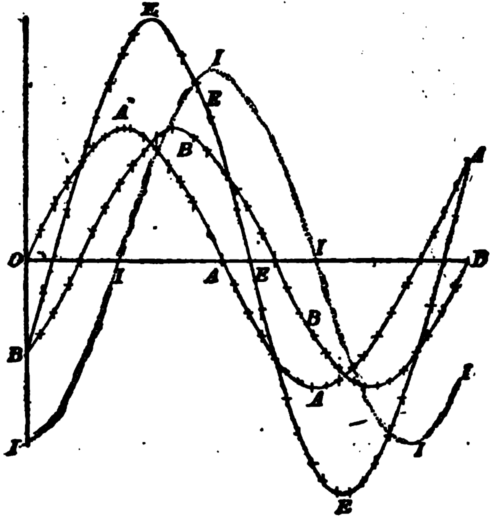
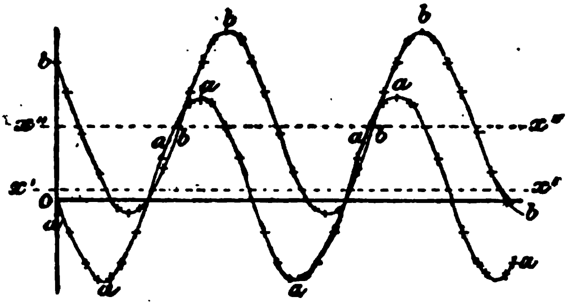


Fig. 446, which has been obtained thus from Fig. 445. Here the curve *a a a* refers to machine A, and *b b b* to machine B. The total work is obtained by measuring the area included between each curve and the axis of abscissæ, remembering that areas *below* the axis are to be reckoned as *negative*, and arithmetically deducted. A moment's inspection of these curves will show that machine B is doing more work than machine A. In fact, the curve *a a a* is symmetrical about the horizontal axis $x' x'$, whereas the curve *b b b* is exactly similar to it, but is symmetrical about the higher axis $x'' x''$, and therefore the positive area included between it and the axis of time is necessarily greater than that for the curve *a a a*. The *lagging* machine B has therefore most work thrown upon it, and will consequently be retarded; thus the lag will be increased, and the resultant electromotive-force, and consequently the current, thereby diminished. But that the tendency will still be towards further lagging is shown in Figs. 447, 448, which are drawn in the same way and to the same scale as Figs. 445 and 446, but with increased lag of machine B. The lag will therefore continue to increase, and the resultant electromotive-force and current to diminish, until such time as the electromotive-forces of the two machines differ in phase by exactly half a period, and therefore directly oppose one another. In this case the resultant electromotive-force will be continually zero, and therefore no current will flow. Figs. 445 and 447 will be reduced to Fig. 449. This condition of affairs is stable, since if anything disturbs the exact opposition of phase the electrical action will tend to re-establish it.

Fig. 448.



Another deduction from the above proof is that the machines will theoretically work perfectly well in parallel. For let A *a* (Fig. 450) represent the collectors of machine A, and B *b* those of machine B; then, as shown above, if these are joined, A to B, and *a* to *b*, as in the dotted lines of the figure, no current will flow, and if an arc-lamp be placed in *b a* or B A it will not light up. In fact, A and B are both at their maximum positive potential simultaneously, and at the same instant *a* and *b* are at their maximum negative potential. But this is exactly the state of affairs which will enable us to obtain a current through the circuit P R *p* joined on to the wires A *a* and B *b* at the points P and *p*. With this arrangement the machines are working in parallel through the circuit P R *p*.

FIG. 449.

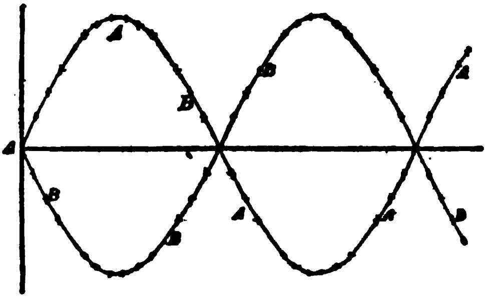
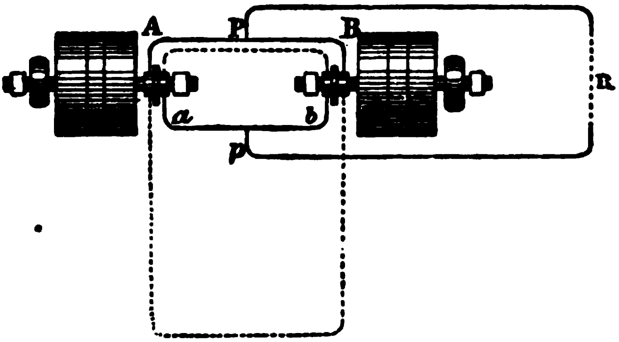


FIG. 450.



A still further deduction is that an alternate-current machine can be used as a motor. In this case machine B (the *lagging* machine) is the generator, and is doing positive work upon the current, whereas machine A is doing negative work upon the current, *i. e.* is receiving energy therefrom, and is therefore acting as a motor. The conditions are that the lag of one electromotive-force behind the other shall be greater than a quarter period, the lag of the current being as usual either equal to or less than a quarter period behind the *resultant* electromotive-force. These statements are readily proved by re-drawing Figs. 445 and 446 under the above conditions. Here is the result in Figs. 451 and 452.

FIG. 451.

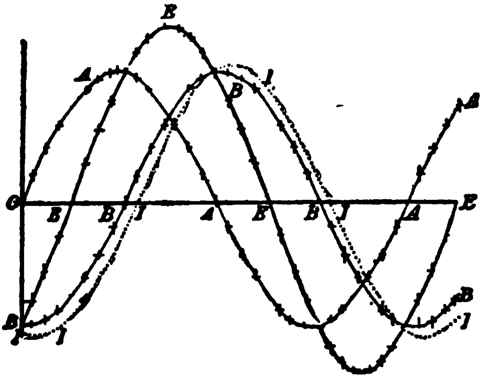
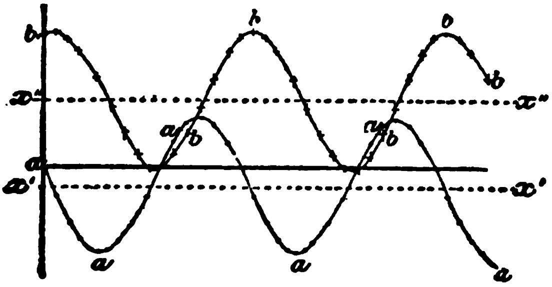


FIG. 452.



A more curious result still is that A can be driven as a motor by B *even if its electromotive-force is greater than that of* B. The proof is precisely the same as that just given, and is left for the student to work out for himself as an exercise.

All the curves given are for the same pair of machines, running at the same speed throughout, and with the same total resistance and inductance in the outer circuit. The lag of the current behind the resultant electromotive-force is therefore the same in each case (see p. 627).

It is scarcely necessary to say that the analytical proofs are in perfect accord with the graphic ones. A further result of the analytical method, which is not so amenable to graphic treatment, is that the energy wasted in eddy-currents in the iron when the machine is *short circuited* is *less* than when it is running on *open circuit*, and therefore the machine will be cooler when used to generate a current than when allowed to run without doing so. This fact has long been well known in connexion with alternating-current machines, and is well illustrated by the following experiments made by Dr. Hopkinson on a De Meritens machine:—

Power given to machine as measured on belt . .	3·1	4·8	5·6	6·5	5·4
Electric power developed	0·7	3·4	4·3	5·7	3·4
Power lost	2·4	1·4	1·3	0·8	2·0
Mean current in amperes	7·7	38·6	51·7	73·6	151

It will be noticed that the loss of power is *least* with maximum load.

The above conclusions have been brought by Dr. Hopkinson and Prof. Adams to the test of experiment with the three large De Meritens machines used for the investigation on "Lighthouse Illuminants" at the South Foreland.

Two of the machines were connected in parallel and clutched together until they had attained their usual speed, when they were unclutched and each was driven by its own belt. The electromotive-force on open circuit remained steady, the machines continuing to rotate in unison, and was the same as that of one of the machines when tested by itself. No current passed along the connecting wires. The circuit P R *p* (Fig. 450) was now closed through an arc-lamp; the machines continued to run as steadily as before, although a large current of 221 amperes was passing through the arc. Lastly, the lamp circuit was broken, the machines were short-circuited on one another, and the belt was thrown off one of them; it continued to run at the same steady speed, being driven as a motor by the current from the other machine. Other experiments were made, all confirming the theoretical conclusions.

Dr. Hopkinson has pointed out that, assuming the adequacy of his equations, which suppose all magnetizing or demagnetizing actions in the armature to be absent, it results from his equations that two alternators running in parallel will tend best to keep in phase by mutual control when the ratio of their internal resistance to their coefficient self-induction is equal to 2 π times the frequency. This proposition has been supposed by some to imply that the presence of self-induction in the armature is good for alternate-current machines, in order to assist them to run in parallel. It was therefore supposed that those machines having iron cores in their armatures were preferable to those having no iron. Indeed, Mr. Kapp[1] suggested at one time that to fit alternators for parallel running, either their armature resistance or their self-induction would have to be increased, thus reducing the efficiency of the plant. Against these views Mr. Mordey[2] has very clearly laid down the proposition that for successful parallel running both resistance and self-induction should be as small as possible, and all armature reactions should be as far as possible obviated by employing massive powerful field-magnets. He constructed two alternators which conformed to this leading principle, each capable of yielding 17 to 20 amperes at 2000 volts when running at 650 revolutions per minute, and making a frequency of 100 alternations per second. With these two machines he conducted a number of convincing experiments, which are described in the important paper which he communicated in 1889 to the *Institution of Electrical Engineers*. These two machines (each separately excited) ran perfectly when switched in parallel with one another: (1) when both were first brought to equal voltage and into agreement of phase, with or without a load of lamps on the circuit; (2) when excited to 1000 and 2000 volts respectively and separately brought into agreement of phase; (3) when excited to 1000 and 2000 volts respectively and switched together when out of phase, a sufficient current passing for an instant from one to the other to produce concordance of phase; (4) when separately excited to 2000 volts each, and switched together out of phase; (5) when after running together in parallel one was suddenly disconnected from its driving engine; (6) when after running together in parallel, steam was suddenly shut off from one engine; this alternator then running perfectly as a motor and driving the engine and shafting. In all these cases there was perfect synchronism. The change of phase needful to convert a leading into a lagging[1] machine need be only through a small angle; but as in the alternators of Mordey's pattern (p. 676) the momentum of the moving parts is very great, nothing but a very considerable rush of current for an extremely short time would suffice to bring about the needful change of phase. Accordingly, Mr. Mordey holds that self-induction and resistance and anything else that could retard, check, or choke the free rush of current would be detrimental to the prompt and efficient mutual controlling action of the two machines. That a strong mechanical action does take place when an alternator is suddenly converted from generator into motor, and is compelled to change its phase, is evidenced by a curious grunting sound which it emits at the moment. Sir William Thomson has expressed the opinion[2] that the armature current may, under the various phase-relations, produce considerable quasi-permanent magnetizing and demagnetizing actions which affect the mutual control. Experience, however, shows that if two machines are run with very weakly excited field-magnets their synchronizing power is practically nil, whereas when strongly excited their synchronizing power is enormous. This single fact shows that the ability to maintain synchronism depends on the forces which are due to the drag of the magnetic field on the armature conductor carrying currents. It therefore proves that *the essential fact in the maintenance of synchronism is the interchange of currents between the two machines, which interchange of current always sets up forces tending to so alter the phase-relations as to reduce such currents to a minimum.* This proposition, which is a mere extension of the universal law of action for electric motors (see p. 589), is applicable not only to those cases where one of the two machines is acting as a motor, but to the cases where the machines are both acting as generators. When two machines are being used as generators, in parallel, it is always possible to control the division of the load between them by controlling the amounts of exciting current supplied to their respective field-magnets. They adjust their own phase-relations to suit. It is therefore clear that the question whether the ratio of self-induction to resistance has any particular value, is of quite trifling importance in the question of synchronization. For this ratio is practically the same, no matter whether the field is strong or weak, and yet the synchronization is entirely dependent on the field being strong.

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[1] *Proc. Inst. Civil Engineers*, xcvii. 14, 1889.

[2] *Journal Inst. Electrical Engineers*, xviii. 591, 1889.

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[1] These terms refer, as above, to the leading or lagging of the electromotive-force with respect to the current.

[2] *Journal Inst. Electrical Engineers*, xviii. p. 667, 1889, in the discussion of Mr. Mordey's paper.

For further information on this subject the reader is referred to an article by Dr. G. Schmidt, in *Centralblatt für Elektrotechnik*, ix. 440, 1887, dealing with methods of indicating difference of phase in alternate-current dynamos, by Elihu Thomson, in *Electrical World*, vol. ix. p. 258, May 1887, and vol. xi. p. 39, Jan. 1888.

CHAPTER XXIV.

ALTERNATE-CURRENT MOTORS.

As pointed out on p. 694, an ordinary alternate-current generator may also serve as a motor having the following peculiarities: (1) it will not start itself, but must be first run up to its proper speed, and then switched into circuit; (2) when once so started it will run in absolute synchronism with the generator at all loads within its range of work. Many attempts have been made to devise self-starting alternate motors, there being now four well-established classes of such machines. The classification adopted is based upon that of M. Hospitalier.[1]

CLASS I.—*Synchronous Motors.*

This class includes all ordinary alternators having field-magnets either of permanently magnetized steel, or separately excited from some independent source, or excited from their own currents by the intervention of a special commutator, as in the self-exciting alternators of Wilde (p. 646), of Zipernowsky (p. 662), and of Elihu Thomson (p. 660). The essential feature of these machines consists in the fact that the field-magnet remains of unvarying polarity. Ordinary two-phase alternators are not self-starting as motors: but multi-phase alternators, when fed with currents in appropriate phases, are self-starting provided the initial load is not too great, since the successions of phase in the armature windings produce a rotating magnetic field which causes the motor to rotate at first slowly, then more rapidly, up to complete synchronism.

The properties of ordinary alternators as synchronous motors have been studied by Wilde,[1] Hopkinson,[2] Adams,[3] and Mordey.[4]

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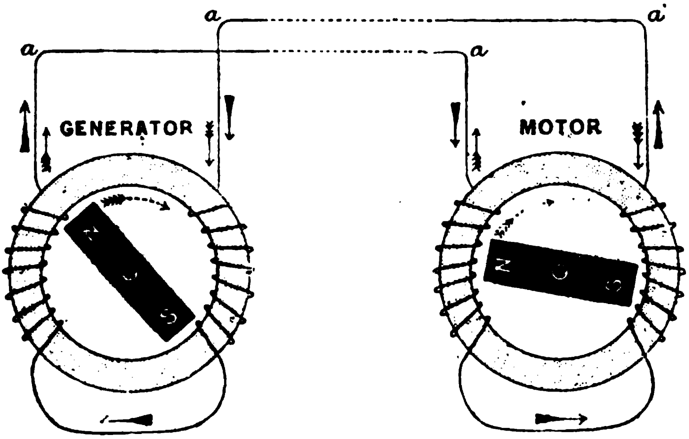
[1] *Société Française de Physique*, July 17, 1891.

Consider the case typified in Fig. 453, in which two similar machines are used as generator and motor. In these the field-magnet rotates within a laminated ring-wound armature. The motor is supposed to have been started and to have settled into almost complete opposition of phase to the generator; the current being represented as in phase with the electromotive-force of the generator and opposed to that of the motor. Two lines are needed, one for the out-going, the other for the return current. Should the motor lag in consequence of an increase of load, more current will flow, making the torque greater.

FIG. 453.



TRANSMISSION BY TWO-PHASE ALTERNATORS.

CLASS II.—*Laminated Field Motors.*

As pointed out on p. 590, the direction of rotation of any ordinary series-wound motor is the same irrespective of the direction of the current supplied to it. Hence such a motor ought also to run when fed with alternating currents.[1] But in this case it is essential that the field-magnets be carefully laminated; otherwise they will be over-heated with currents induced in the solid iron. Such laminated motors have been successfully used on a small scale. Shunt-wound laminated field-motors should similarly run with alternate currents: but the great self-induction of the magnet-circuit tends to introduce a phase-complication. Mr. Ll. B. Atkinson has suggested[2] several combinations of such motors to secure uniformity of running. In all two-phase motors there is of necessity a discontinuity in the driving forces, seeing that twice in each alternation the current dies down to zero. The effect of this on the motor is the same as though there were simultaneously acting a constant torque and a rapidly oscillating torque tending to rack the coils backward and forward. Further, the rapid reversal of the magnetism of the iron in the field tends to waste power by hysteresis. To minimize this source of loss, Mordey[3] has proposed to pass the exciting current through a commutator on the shaft of the machine, so that as the motor acquires speed the frequency of the alternations in the motor itself is reduced, until synchronism is attained, the current then being an intermittent direct current, and the torque being a maximum. Another mode of avoiding this loss is to omit all iron from the machine. Such a motor is of relatively small power; but it is used with great success in Elihu Thomson's electric motor.

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[1] *Proc. Lit. Phil. Soc. Manchester*, Dec. 1868; also *Phil. Mag.*, Jan. 1869.

[2] *Journal Soc. Teleg. Engineers*, xiii. 496, 1884.

[3] *Ibid.*, p. 515, 1884.

[4] *Ibid.*, xviii. 592, 1889.

Another sub-class of motors under this heading is based upon the forces set up by the reaction of eddy-currents on the field which generates them. The classical experiments of Elihu Thomson[4] on the repulsions observed in closed circuits when placed in an alternating magnetic field, led him to suggest a form of motor in which the circuits of field-magnet and armature are entirely disconnected from one another. This machine may be regarded as a species of transformer in which the rotation is produced by a series of mechanical reactions between the currents in the primary coil (acting as field-magnet) and the secondary coil acting as armature. A closed coil in such a field always tends to move so that the magnetic flux through it is a minimum. If an ordinary ring or drum motor be taken (with laminated field), its field-magnet disconnected from the armature and excited by the alternate-current, and the brushes then simply connected together (so as to close the armature-circuit on itself) and advanced through about 45°, the motor will run and be self-starting.

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[1] See remarks of Alex. Siemens, *Journ. Soc. Teleg. Engineers*, xiii. 527, 1884.

[2] Specifications of Patents, 16,852 of 1888, and 7895 of 1889.

[3] *The Electrician*, xxiii. 346: also Specification of Patent, No. 15,555 of 1887.

[4] *Electrical World*, ix. 258, May 1887: also *The Electrician*, xxv. p. 35 *et seq.*, May 16, 1890, in a series of articles by Prof. Fleming. See also an abstract account in the author's work on *The Electromagnet*, p. 338.

CLASS III.—*Multi-phase Rotatory Field Motors.*

In 1885 was propounded, by M. Marcel Deprez, the geometrical notion that a rotating magnetic field might be produced by the combination at right angles of two alternating currents (varying in sine-functions of the time) which differed by a quarter period from one another in phase. In 1888 the idea of producing a rotatory field by the use of two currents differing in phase, independently led Professor G. Ferraris,[1] of Turin, Mr. Nikola Tesla,[2] of New York, and M. Borel,[3] to the production of rotatory-field motors. Tesla in particular worked out a large variety of forms on this plan and gave them practical shape. The practical importance which rotatory-field motors have since attained renders needful a careful exposition of this principle of action.

Theory of Rotatory Field.—Referring to Fig. 395, p. 620, in which a point is supposed to move at a uniform speed round a circle, let the angle P O M through which the radius O P has turned from the zero point be called θ, then P M $=$ sin θ, and Q P or O M $=$ cos θ, if the radius be taken as unity. The circular motion, if projected on a vertical line will give a simple-harmonic vertical motion, or if projected on a horizontal line will give a simple-harmonic horizontal motion.

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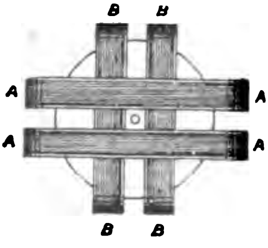
[1] Rotazioni elettrodynamiche, *Turin Acad.*, xxiii. March 1888.

[2] *Electrical World*, x. 281, June 1888; xv. 250, 1890 ; xvi. 101, 1890.

[3] *La Lumière Electrique*, xxix. 51, 1888.

Every engineer knows how readily a rotatory motion can be converted into two rectilinear motions at right angles to each other by causing a crank-pin to operate two connecting-rods. And in this case the two rectilinear motions will differ in phase by a quarter period, for one will be at the middle of its stroke when the other is at the end. Conversely, it is possible to produce a circular motion by compounding together at right angles two rectilinear (simple-harmonic) motions that differ exactly one quarter period in phase, so as to produce a circular one. If the difference of phase is not exactly a quarter period, the resulting motion will be elliptical instead of circular. When two alternating currents differing exactly a quarter period in phase are carried around two magnetizing coils placed at right angles to one another, thus tending to produce two separate magnetic fields alternating across one another, their conjoint action will result in a rotating magnetic field. Ferraris found that in such a field not only will pivoted magnets rotate, but masses of iron, both solid and laminated, also disks and cylinders of copper, the drag on these being due to the eddy-currents generated in them precisely as in the classical experiments of Arago, in which copper disks were set into rotation in the presence of a rotating magnet. Fig. 454 illustrates a simple form of Ferraris's motor having a copper cylinder pivoted within two sets of coils A A and B B which lie at right angles to one another. If the two independent magnetizing forces follow sine-functions, and are exactly at right angles and differ exactly a quarter period in phase, the torque will be uniform. But if the phase-difference is not an exact quarter period, or the coils not exactly at right angles, the torque will have two maxima and two minima in each period, corresponding to the elliptical motion in the mechanical analogue.

FIG. 454.



SIMPLE ROTATORY FIELD MOTOR.

ILLUSTRATIONS OF ROTATORY FIELD TRANSMISSION.

In Fig. 453, p. 701, the case of ordinary two-phase alternators was illustrated. In this case there is a mere oscillatory field, magnetism in each part of the armature simply alternating in polarity. Such an alternator has dead points, and cannot start itself.

Four-phase Currents.—Now suppose that beside the two coils A A′ on each machine there are wound other two B B′ between the former pair, and that these are connected through a new pair of lines *b b* and *b′ b′*, Fig. 455. It is clear that a second set of alternating currents will be set up in B B′ which will be exactly a quarter-period in phase behind those in A A′. In fact the two currents will be represented by the two waves of Fig. 456. The electromotive-force in A will be greatest just when the pole of the magnet is passing its middle, for at that instant the rate of change in the magnetization of its core is a maximum. And the maxima for the B coils will correspond to the zeros for the A coils and *vice versâ*. The currents in the A coils of the motor, tending to drag forward the pole of the field-magnet, will not have died down to zero

FIG. 455.

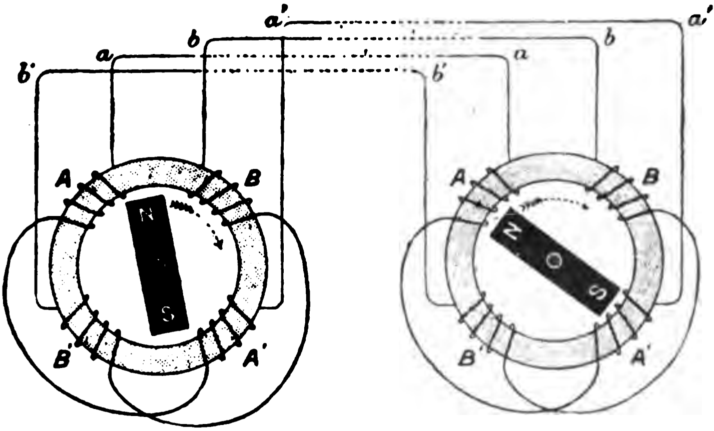
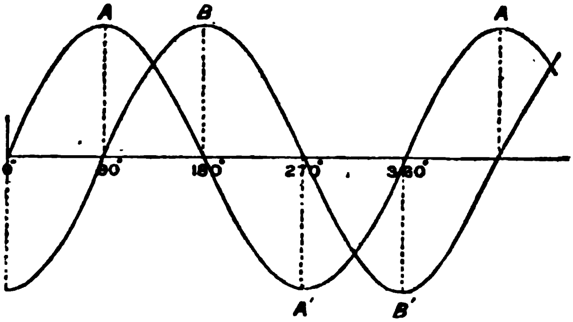


ILLUSTRATION OF FOUR-PHASE TRANSMISSION.

before the currents in the B coils will have already begun; so that there is no dead point. It is easy to see that in the motor there will be a regular displacement around the ring of the resultant poles. At the moment when the current in A A′ is at a maximum that in B B′ will be zero, and the magnetizing action of A A′ will be to produce two double-poles in the ring at opposite ends of a diameter right under the middle of the B B′ coils. As the current in A A′ dies down that in B B′ begins and increases, and therefore shifts the pole forward. When the currents in A A′ and B B′ have become equal A and B will act together as one coil, while A′ and B will act together as another coil, the resulting poles lying now between B and A′ on the right and between B′ and A on the left. When the B current is at its maximum the poles will lie right under the middle of the A coils. A pair of travelling poles are therefore produced in the motor ring by the currents coming from the generator, and the magnet in the motor is continually trying to catch up these travelling poles. The motor will be self-starting if its magnet is not too powerful, and will run up in speed until synchronism is attained.

FIG. 456.



TWO ALTERNATE CURRENTS DIFFERING BY A QUARTER PERIOD.

Since there is an actual production here of a travelling polarity in the ring of the motor, it follows that any mere mass of iron, a cylinder for example, placed in the rotating field will be set into rotation, though not necessarily synchronously. And a cylinder of copper would be dragged round by the eddy-currents induced in it. But if such eddy-currents were permitted to circulate at random in the mass of copper there would be much waste of power in heating, since the only useful currents for driving are those that flow at right-angles to the magnetic lines and at right-angles to the direction of motion, or, if oblique, their resolved parts in this direction. Hence it is better to make the moving part as an iron core surrounded by appropriate closed coils of wire within which the induced currents are confined. Such closed-circuit windings have been used by Tesla and others. Tesla's motors have been in successful use in the States, the standard size being a 7 HP. motor weighing 340 lbs., and having a nett efficiency over 85 per cent. A special form due to Dobrowolsky[1] consists of a cylinder of iron within the periphery of which are embedded—with or without insulation—a number of stout copper conductors lying parallel to the axis, their ends being united together so that they form closed circuits. A mere disk of copper at each end—forming with the conductors a sort of squirrel-cage of copper filled with iron—answers excellently. Or each conductor on the periphery may be joined by a connector (as in Fig. 457) to each of the other conductors which lies in the corresponding position of symmetry. Dobrowolsky preferred, in the motor used for the Frankfort transmission in 1891, to invert the arrangement, fixing the closed copper circuits and their core, and using as the rotating part that corresponding in Fig. 458 to the ring. It had three separate circuits not closed within the

Fig. 457.

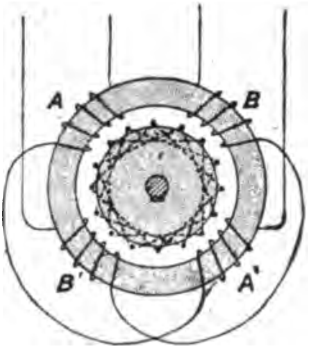


Diagram of a Rotatory Field Motor.

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[1] *Elektrotechnische Zeitschrift*, xi. 341, 1890; also *Electrical World*, xv. 442, 1890.

machine but communicating with external resistances through contact rings. It was thus possible to prevent the enormous rush of induced current which otherwise might occur at starting, and which, though it would not harm the motor, might have an injurious reaction on other parts of the system. The external resistance could be cut out when the motor had got up its speed.

When such rotating combinations of copper and iron are used it becomes a question which part of the machine should be considered as armature, and which as field-magnet. If the ring is regarded as armature, then the copper and iron combination must be looked upon as a field-magnet which is self-magnetized by the eddy-currents in the copper, and which is continually trying to catch up the rotating poles outside it so as to reduce those eddy-currents to a minimum and keep its magnetic polarity constant. If, however, the ring be looked upon as the equivalent of a rotating magnet, then the combination of copper and iron must be considered as an armature in which currents are induced, and which is driven by the reaction of these currents.

So far it has been supposed that the two circuits of the A and B coils were kept separate, requiring four wires. As a matter of fact, only three wires are necessary; for a single common return might be provided for the *a* and *b* wires instead of two separate wires, the current in the return being the algebraic sum of the currents in *a′* and *b′* at every instant, and therefore having a maximum value 1·4 times as great.

Three-phase Currents.—Another mode of using three wires is to generate three equal currents differing in phase by 180° or by 60° from one another. The three-phase alternator of Brown, used at Lauffen, was described on p. 688. Three-phase motors have been suggested by Tesla and others. An illustration of the three-phase system is afforded by Fig. 458, in which the rings are wound with three coils all joined at their ends and united to the three lines. In this case the current in any one line is equal to the algebraic sum of the currents in the other two, and, with the arrangement shown, the phase of the currents in any one of the lines is intermediate between the phase of the currents in the two coils feeding it. For example, the current in *a* is intermediate in phase between those in coils P and Q in the generator. Further, in the motor the current in P is intermediate in phase between the currents in *c* and *a*. As the magnet rotates in the generator a travelling pole will be produced in the ring of the motor as before. It will be noted that the coils here constitute a closed circuit. There are indeed several ways of connecting up three coils so as to produce the rotatory effect, the following being possible: (1) each of the three coils might be independently joined by two wires to the ends of the three corresponding coils, requiring six lines; (2) three ends of the three coils might be independently joined by three wires to the three corresponding ends of the coils in the motor, their three other ends being united to a common return line, so involving four wires; (3) the three coils *a*, *b*, and *c* may be simply joined at a common junction J (Fig. 459), from which they branch star-wise each to its own line; (4) the three coils may be joined as *p*, *q*, and *r* in Fig. 460, in a closed

FIG. 458.

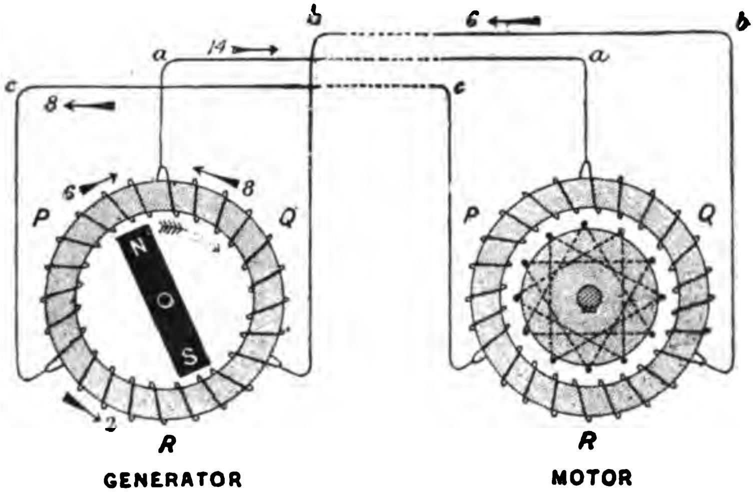
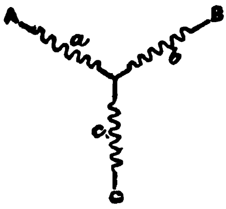


ILLUSTRATION OF THREE-PHASE TRANSMISSION.

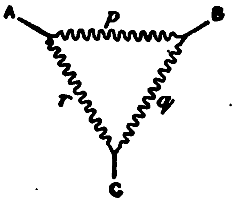
mesh joined with the three lines at its corners. In this case the phases of the currents in *p*, *q*, and *r* are intermediate between those of the three currents in the lines; (5) six coils may be used as in Fig. 461, which shows the way of getting a six-phase effect out of a three-phase current by combining the star and mesh arrangements; (6) by merely winding a coil left-handedly instead of right-handedly the phase of its magnetizing force is reversed. For example, a reversed coil inserted in *a* (in Fig. 459) would give an effect differing 180° in phase from *a*, and therefore intermediate between *b* and *c*. By constructing a star with reversed coils in each branch, six phases can thus be got from a three-phase current.

FIG. 459.



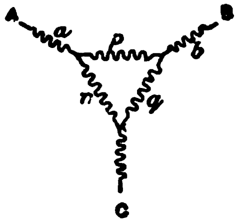
STAR COMBINATION.

FIG. 460.



MESH COMBINATION.

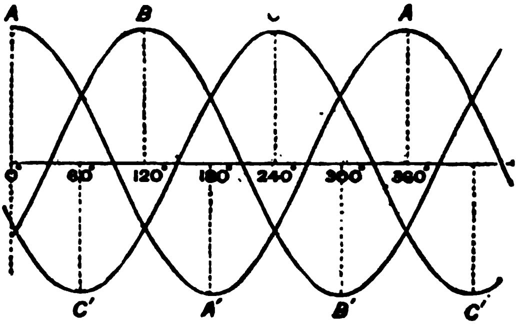
FIG. 461.



STAR AND MESH COMBINATION.

The mode in which the three currents overlap in phase is shown in Fig. 462, the phase difference being here 120°. Three currents with phase-difference 60° will also serve for rotatory work, and can be converted into three of 120° by merely inverting the connexions of one of the coils at each end. Dobrowolsky, who applied the name *Dreh-strom*, or *rotatory current*, to the system of currents alternating in periodic succession of phases and producing a rotatory field, has urged the superiority of the three-phase arrangement over four-phase, on the ground that if one constructs for such curves as Figs. 455 and 462, the resultant curve, the latter will show less variations in the case of the three-phase combinations, the fluctuations of the ordinates being 40 per cent. in the resultant of the four-phase and only 15 per cent. in that of the three-phase. This assumes the waves to be of sine form; which is not necessarily true. Moreover, adding sine and cosine ordinates is not the same thing as forming their true oblique resultant, which is their vector-sum, by the ordinary rule for compounding forces.

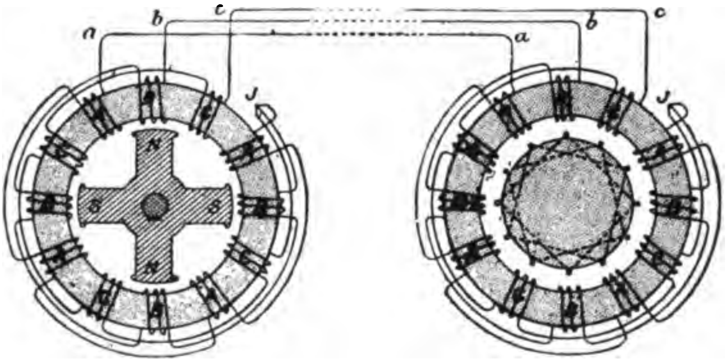
Fig. 462.



Three-phase Current Curves.

A further illustration of the three-phase current is afforded by Fig. 463, in which the rings are multipolar, being wound

Fig. 463.



Three-phase Multipolar Transmission,

with twelve coils, producing four rotating poles. In this case there are both right-handed and left-handed coils, giving six phases of currents at 60° apart in period. The connexions constitute a star-combination, the three circuits having a common junction J at each end.

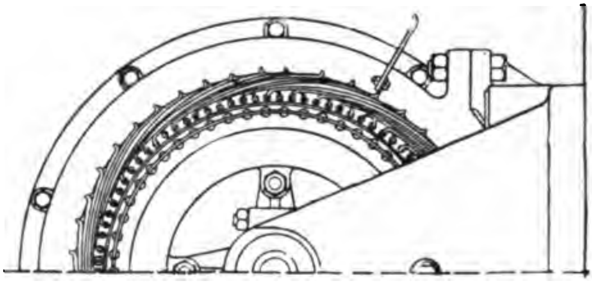


Fig. 465.

Half End-Elevation.

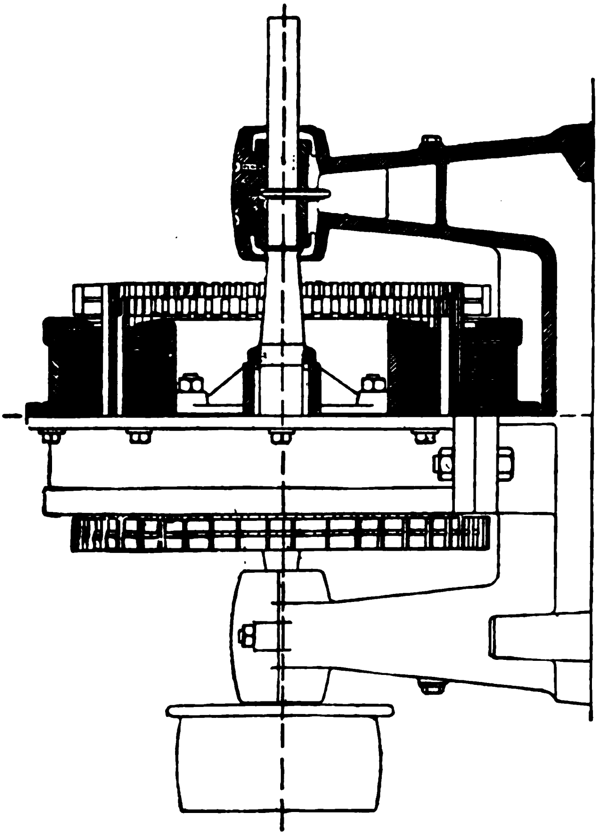


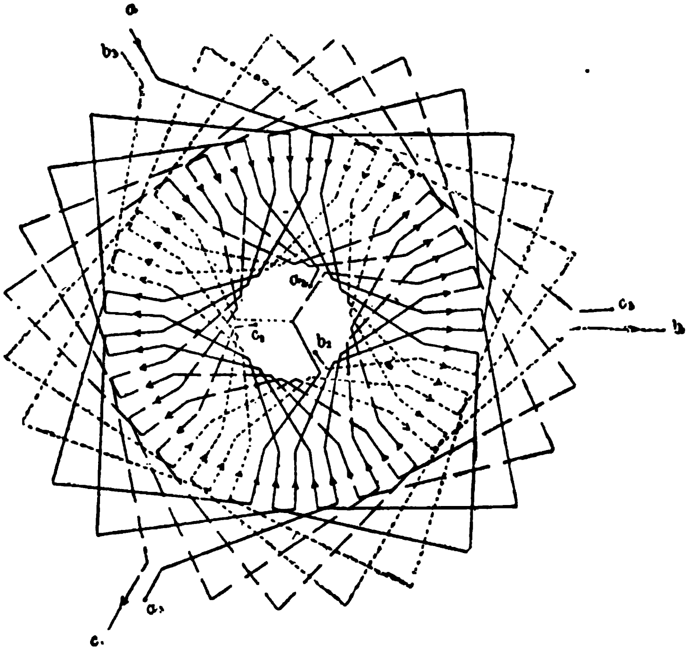
Fig. 464.

Brown's Three-phase Motor, Elevation.

Brown's Three-phase Motor.—No details have been published respecting the 60 horse-power three-phase motor used in the Frankfort transmission, which was constructed by the Allgemeine Elektrizitäts Gesellschaft of Berlin, from the designs of Dobrowolsky.[1] In the absence of such information, some drawings are here given of another somewhat similar motor designed by Mr. C. E. L. Brown.[2]

This motor gives out about 20 horse-power at 1200 revolutions per minute, when supplied with three-phase currents at 50 volts alternating with a frequency of 40.

FIG. 466.



BROWN'S THREE-PHASE MOTOR: SCHEME OF WINDINGS.

The general build of this motor recalls that of the three-phase alternator used at Lauffen, all the copper conductors being round bars which pass through perforations in the core disks.

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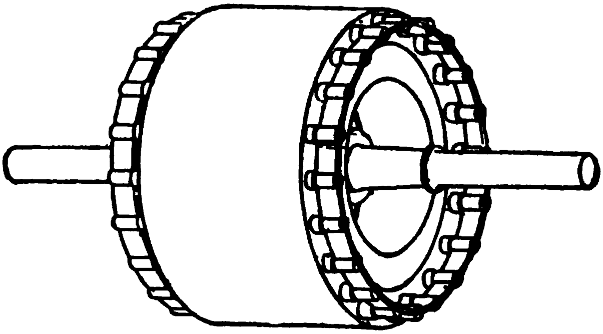
[1] See *Electrical Review*, xxix. 556, 1891.

[2] *Elektrotechnische Zeitschrift*, xii. 657, 1891. See also *The Electrician*, xxvii. 657, 1891.

In the outer stationary part are 90 conductors of about 40 sq. mm. section, each joined by end connectors of curved copper strip, which connect over spans of a little less than 90° in a wave-winding according to the scheme indicated in Fig. 466. This produces four travelling poles. The rotating part, which is also constructed with perforated core-disks, has 54 copper rods, each of 100 sq. mm. area. These are simply connected together at their ends by copper rings. There are 95 kilos. of copper in the rotating part, and 20 in the fixed windings. The weight of iron in the rotating part is 70 kilos., in the fixed part 100 kilos. There are no sliding contacts of any kind, and the whole motor runs quite cool. The difference in speed between no load and full load is about 3 per cent. The torque at starting was over 40 meter-kilogrammes. The total weight is about 420 kilos., and the commercial efficiency about 90 per cent.

FIG. 467.



ROTATING PART OF BROWN'S MOTOR.

Other Multi-phase Motors.—In another type of three-phase motor by Siemens and Halske, the three currents pass first through coils on an outer ring, producing a rotating field, and then are led by three brushes bearing on a commutator into a rotating armature. Schuckert & Co., Haselwander, Bradley, and Wenström have also constructed multi-phase motors.

CLASS IV.—*Rotatory Field Motors with Two-phase Currents.*

It is possible by various means to produce a rotatory field without resorting to three or four-phase currents. Many years ago De Fonvielle discovered that an iron disk pivoted within a coil supplied with an alternate current was maintained in rotation if once started in either direction.

Ferraris produced rotation in his motor by connecting one of the pairs of coils in the circuit of an ordinary alternate current, whilst the other pair were connected as a shunt to the circuit, with an inductive resistance included in order to retard the phase. Borel attained a similar result by using iron cores in one pair of coils. Schallenberger, in the mechanism of his meter, introduces a neat principle. The alternate current is led into two large coils which pass under and over the rotating iron wheel. Within these coils, and also surrounding the wheel, are two other coils, closed on themselves, made of brass stampings. In these coils secondary currents are induced, and these are different in phase by not quite 180°. But these secondary coils do not lie parallel with the primary coils, being set purposely at an angle of about 40° to them. Here, then, are two alternate currents, in different phases, acting at an angle. In the Borel-Ferranti meter another device is adopted. The pivoted wheel of iron or copper is placed between two field-magnets of laminated iron, each provided with a single elongated curved pole-piece.[1] The limbs of this field-magnet carry coils for the alternate current; whilst upon the prolongations or horns are placed closed windings of copper in which the alternating magnetic fluxes set up eddy-currents. The effect of these eddy-currents is to oppose the change of the magnetism in the core; with the result that they retard the propagation of the magnetic pole along the cores towards the tips of the horns, producing the phenomenon of an alternate succession of north and south poles travelling along the pole-pieces toward the tip, and there dying out.

A mode of splitting an alternate current into two alternate currents differing in phase from one another has been proposed by MM. Hutin and Leblanc,[1] for use in a rotatory field motor. When the current from the line arrives at the motor it is led into a divided path, into one branch of which a condenser of suitable capacity has been inserted, whilst into the other branch a coil possessing self-induction is intercalated. The former tends to accelerate[2] the phase of the current in its branch, whilst the latter retards the phase in the other branch, thus producing the desired phase-difference.

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[1] *Electrician*, xxv. 32, 1890.

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[1] *La Lumière Electrique*, xl., 1891.

[2] A condenser acts as a negative and reciprocal self-induction. Thus, whilst a self-induction L tends to produce a lag such that $\tan \phi = 2 \pi n L \div R$, a condenser of capacity K tends to produce a negative lag (*i.e.* a lead) such that $\tan \phi = -1 \div 2 \pi n K R$. See p. 635.

CHAPTER XXV.

TRANSFORMERS.

DURING recent years methods of distributing electric energy have come into vogue, in which, for the sake of economizing the cost of the metallic conductors, distribution is effected at a high electromotive-force or electric pressure from the central generators, and is received at different points by apparatus known as *transformers*, which transform the electric energy supplied to them, and give it out again at a lower electromotive-force or electric pressure.

To comprehend fully the bearing of the matter, it must be remembered that the energy supplied per second is the product of two factors, the current and the pressure at which that current is supplied; or, in our notation,

$$E\,i = \text{electric energy per second (in watts).}$$

The magnitudes of the two factors may vary, but the value of the power supplied depends only on the product of the two; for example, the energy furnished per second by a current of 10 amperes supplied at a pressure of 2000 volts is exactly the same in amount as that furnished per second by a current of 400 amperes supplied at a pressure of 50 volts; in each case the product is 20,000 watts. Now the loss of energy that occurs in transmission through a well-insulated wire depends also on two factors, the current and the resistance of the wire, and in a given wire is proportional to the square of the current. In the above example the current of 400 amperes, if transmitted through the same wire as the 10-ampere current, would, because it is forty times as great, waste sixteen hundred times as much energy in heating the wire. Or, to put it the other way round, for the same loss of energy one may use, to carry the 10-ampere current at 2000 volts, a wire having only $\frac{1}{1600}$th of the sectional area of the wire used for the 400-ampere current at 50 volts. The cost of copper conductors for the distributing lines is therefore very greatly economized by employing high pressures for distribution of small currents.

For transforming from high pressures to low, several kinds of apparatus are known, namely:—

1. *Storage Batteries.*—A large number of these to be charged in series at a high potential: the series afterwards divided up or rearranged so as to discharge larger currents at lower pressure. This system is applicable to direct-current working only, not to alternate currents, and has the advantage of storing the consumer's supply.

2. *Induction Coils*, also called for this purpose *Secondary Generators*, or *Transformers*, or *Converters.*—This system will only answer with alternating currents, which being transmitted through the distributing mains at high pressure, and traversing the primary wires of the induction-coils, set up in the secondary wires currents which feed the separate circuits of lamps at the desired low pressure.

3. *Motor-Generators.*—These are either two separate machines: a motor, adapted to receive small currents at high potential, and be driven by them, and a dynamo, driven by the motor, and capable of generating large currents at low potential; or they consist of single machines having a double-wound armature, one set of windings of fine wire to receive the incoming currents at high potential, and another set, of thick wire, to furnish the outgoing currents at low potential.

4. *Commuting Transformers.*—These are a variety of the last, but neither armature nor field-magnet revolves, the polarity of the magnetic circuit being caused to vary by special commutators.

5. *Condensers.*—It is theoretically possible to employ condensers for transforming alternate currents, but their use is not yet practical.

Storage batteries we cannot here discuss; motor generators will be very briefly touched upon. Induction-coil transformers for alternate currents being a species of dynamo-electric machine, will be dealt with only as such: space does not admit of discussion of the various systems of distribution in which they are employed.

HISTORICAL NOTES ON TRANSFORMERS.

The first induction-coil was used by Faraday,[1] and consisted of a solid iron ring six inches in diameter and seven-eighths of an inch thick, having a primary wire seventy-two feet in length, and a secondary sixty feet in length, coiled around opposite parts (Fig. 471, No. 1). Small modifications were made by Masson,[2] who introduced a bundle of iron wires as core; Pohl,[3] Wright, Callan, Henley,[4] Dove,[5] who examined the properties of various kinds of iron cores and the damping effects of solid metal conductors and tubes; Sinsteden,[6] Magnus,[7] who also investigated the effects of the form of the iron core; Stöhrer,[8] who constructed the vertical pattern of coil; Ritchie,[9] who suggested the use of cloisons or partitions in winding the secondary, where high insulation was wanted; Ruhmkorff,[10] who gave the spark-coil its classical proportions; and Varley,[11] who in 1856 described a form of induction-coil having a laminated and closed magnetic circuit, closely resembling some of the modern forms of transformers. Various suggestions for use of induction-coils in distributing current for electric lighting were made by Jablochkoff,[12] who proposed to place in the circuit of an alternate-current machine, at different points of the circuit, the primary coils of a number of transformers, the secondary coils of which were used to supply lamps of the "electric-candle" type, and by Sir C. Bright,[13] who proposed similarly to distribute currents to vacuum-tube lamps. Jablochkoff, and later Edwards and Normandy,[14] suggested a peculiar construction of copper-strip conductors, set edge-on, in place of round wires in the coils. More practical forms of transformers were suggested by Fuller,[1] and by De Meritens.[2] In 1881 Hopkinson[3] proposed to utilize the self-induction of a coil with iron core, to "choke" the currents of an alternate-current system instead of introducing wasteful resistance. In the same year a very important patent was taken out by MM. Marcel Deprez and J. Carpentier[4] for a system for the economical transport of electric energy by means of tranformers. At the generating station the alternating currents of low potential were to be transformed by means of an induction-coil to currents of high potential, which could then be economically conveyed to a distance through long thin conducting-wires, and there, entering the fine wire primary coil of another transformer could be transformed down to low potential suitable for the lamps or motors. In 1882, Gravier[5] suggested the motor-dynamo as a transformer for continuous currents, a suggestion which had been partially anticipated by Sir W. Thomson[6] and by Gramme.[7] This suggestion was generalized in 1883 by Cabanellas,[8] and systems of distribution on the same plan were independently proposed by Edison,[9] and by Lane-Fox.[10] In 1882, Gaulard and Gibbs[11] revived the use of alternate-current distribution by induction-coils; their first patent proposes a coil of Ruhmkorff type. Their second patent[12] states that in their invention the alternate current in the primary circuit was to be maintained of constant strength, while its electromotive-force was varied, according to the demand on the secondary circuits. This implies distribution in series; in the same year they revived the construction of induction-coils with sheet-copper conductors set edge-on to the core under the name of "secondary generators." In 1883, Kennedy used a modified Gramme ring as a transformer; and in 1885, Deri and Zipernowsky[13] proposed the use of transformers for effecting the self-regulation of the alternate-current dynamo, and revived the use of induction-coils having laminated and closed magnetic circuits. In the same year Ferranti[1] brought out transformers constructed of iron strips. Kennedy[2] had proposed to make the distribution at a constant potential, a method which has been adopted by Zipernowsky, Ferranti, and subsequently by Gaulard and Gibbs, and by Westinghouse in the United States, and which is nearly self-regulating. Improvements in details of construction have been made by Kapp[3] and Snell, Mordey, Westinghouse, and Statter. Swinburne has advocated the use of open circuit transformers as less wasteful of energy at light loads. Recent improvements in motor-generators are due to Scott and Paris,[4] R. P. and J. S. Sellon,[5] and J. Swinburne,[6] the latter of whom suggests machines adapted for transforming from a circuit supplied at constant current to a secondary circuit fed at constant potential.

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[1] *Experimental Researches*, i. 7, 1831.

[2] *Ann. Chim. Phys.* lxvi. 5, 1837; and iv. 129, 1842.

[3] *Pogg. Ann.*, xxxiv. 185, 500, 1835.

[4] *Annals of Electricity*, v. 349, 1840; vii. 322, 1841.

[5] *Pogg. Ann.*, xlix. 72, 1840; lvi, 251, 1842.

[6] *Ibid.*, lxxxv. 465, 1851; and xcvi. 306, 1855

[7] *Ibid.*, xlviii. 95, 1839.

[8] See Wiedmann's *Lehre von der Elektricität*, iv. 339.

[9] *Phil. Mag.*, xiv. 239, 480, 1857.

[10] *Comptes Rendus*, xxxvi. 649; and xxxvii. 801.

[11] Specification of Patent, 3059 of 1856.

[12] *Ibid.*, 1996 of 1877.

[13] *Ibid.*, 4212 of 1878.

[14] *Ibid.* 4911 of 1878.

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[1] Specification of Patent, 5183 of 1878.

[2] *Ibid.*, 5257 of 1878.

[3] *Ibid.*, 3362 of 1881.

[4] *Ibid.*, 4128 of 1881.

[5] *Ibid.*, 1211 of 1882.

[6] *Rep. Brit. Assoc.*, 1881.

[7] *Comptes Rendus*, Nov. 23, 1874.

[8] *La Lumière Electrique*, iii. 44, and iv. 206, 1883; and Specification of Patent, 2880, 1885.

[9] Specifications of Patents, 3752 and 3949 of 1882; and U. S. Patents, Nos. 266,793, Oct. 31, 1882; 278,418, May 29, 1883; and 287,516, Oct. 30, 1883.

[10] Specification of Patent, 3692 of 1883.

[11] *Ibid.*, 4362 of 1882; and *La Lumière Electrique*, xiv. 40,156, 1884.

[12] *Ibid.*, 2858 and 3173 of 1884.

[13] *Ibid.*, 3379 and 5201 of 1885.

SYSTEMS OF DISTRIBUTION BY ALTERNATING TRANSFORMERS.

These are briefly two in number:— (1) *At constant potential*, the distributing mains branching to the various local points where the transformers supply the lights at low pressure. In this case the primary wires of the local transformers are coils of fine wire of many turns, and are all in parallel across the mains; the secondary coils being of thick wire and of few turns. (2) *With constant current*, the single main circuit going from the primary of one transformer to that of the next. In this case, as the primary wires are in series, they are thicker and of few turns. The first of these systems is suitable for incandescent lighting, the second for arc lighting.

GENERAL PRINCIPLES OF ALTERNATING TRANSFORMERS.

An alternating transformer may be regarded as a species of dynamo, in which neither armature nor field-magnet revolve, but in which the magnetism of the iron circuit is made to vary through rapidly repeated cycles of alternation, by separately exciting it with an alternating current. The primary coil of the transformer corresponds to the field-magnet coil of the dynamo; the secondary of the transformer to the armature coil of the dynamo.

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[1] *Ibid.*, 15,251 of 1885.

[2] *Electrical Review*, xii. 486, June 9, 1883.

[3] *Journal Soc. Teleg. Engineers*, xvii. 96, 1888.

[4] Specification of Patent, 6260 of 1884.

[5] *Ibid.*, 3525 of 1885.

[6] *Ibid.*, 6682 of 1887.

Many of the rules for construction of dynamos apply with equal force to the construction of transformers; for example, the rules concerning insulation, lamination of iron cores, and the like. In all cases where transformers are used with very high potentials, the utmost care must be taken about the complete and efficient insulation of all the wire (and connexions) of the high-pressure coils: it should on no account be wound in alternate layers between the windings of the low-pressure circuit, nor stranded with it into a cable; it should, while properly enclosing the iron circuit, not only be as perfectly insulated, but as completely isolated as may be from the low-pressure wire and from all other metal work in the transformer.

In the alternating transformer, by whatever name called, the function of the iron core is to carry the magnetic lines of force (that are created by the current in the primary coil) through the convolutions of the secondary coil. The rate at which the magnetic lines due to the primary current are cut by the secondary circuit is the measure of the electromotive-force given to the secondary circuit. In order to be able to calculate the amount of cutting of magnetic lines that goes on with various strengths of primary current and various rates of alternation, it is convenient to know the amount of cutting of magnetic lines that takes place when unit current is made to flow, or is stopped in the primary coils. Let M be used as a symbol for this quantity. It will be proportional to the number of turns in the secondary coil, because each turn encircles the iron core and cuts the magnetic lines; it will also be proportional to the number of turns in the primary coil, because, *ceteris paribus*, the magnetism evoked in the iron core is proportional to the ampere-turns that excite it; it will also be proportional at every stage to the permeability of the iron core. We may, in fact, calculate M by the magnetic principles laid down in Chapter VI. Suppose the iron core to form a closed circuit of length l, section A, permeability μ; and that S_1 and S_2 are the respective numbers of turns in primary and secondary. Then, if the primary current is unity (in absolute C.G.S. units, the magneto-motive-force due to it will be $4 \pi S_1$, and the magnetic resistance will be $l | A \mu$. Dividing the former by the latter, we shall have an expression for the number of lines in the core; this multiplied by S_2 gives the amount of cutting of lines by the secondary circuit; or in symbols.

$$M = 4 \pi S_1 S_2 A\mu | l.$$

The name given to this quantity is the *coefficient of mutual induction*. If the current in the primary have the value i_1 (absolute C.G.S. units), then the amount of cutting by the secondary on turning this current on or off will be $M i_1$. And if the rate of increase or decrease of the primary current at any instant is known, this multiplied by M will give the electromotive-force impressed at that instant on the secondary circuit. Now it is obviously advantageous in a transformer that this quantity should be as great as possible, for it is desirable to attain the requisite electromotive-force in the secondary with as little primary current as possible. The conditions are, however, a little conflicting: S_2 must not be made large, on account of internal resistance and cost of copper; but it is clear that a compact magnetic circuit having l small, A large, and the iron of good quality will be of advantage. In the particular case (for series working), where the primary and secondary wires are to carry equal currents, it is clear that for a given total weight of copper, the maximum product $S_1 S_2$ will be afforded when there are equal numbers of turns in the coils, and therefore equal weights of copper. In other cases, provided the wires are proportioned to the currents they have to carry, and that equal heat can be developed in each coil, equal weights of copper is still a good rule, though the numbers of turns in the two coils will be widely different. It has been assumed that there is no magnetic leakage; that all the lines of force created in the core pass through the secondary coils. This assumption is very nearly fulfilled in those transformers in which the magnetic circuit is effectively closed upon itself.

The next important point is that the magnetic lines of force created by the primary current in the core pass through the convolutions of the primary coil itself, and that therefore there will be self-induced electromotive-forces in the primary coil, which will tend to oppose the impressed variations of current. Considerations precisely analogous to those above will show that there will be a *coefficient of self-induction*, which we will call L_1 which represents the amount of cutting, by the primary coils, of the magnetic lines created in the coil when the primary coil carries unit current; and we may calculate, on magnetic principles, as before, the value of this coefficient to be

$$L_1 = 4 \pi \, S_1^2 \, A \, \mu / l.$$

That is to say, L_1 will be large in proportion to the goodness of the magnetic circuit; and (as in the case in transformers for distribution at constant pressure) as S_1 is itself large, L_1 will be enormous. As will presently be seen, this has important results in the automatic action of transformers.

The electromotive-forces induced (by the variations of magnetization of the core) in the secondary circuit will, of course, produce no currents if the secondary circuit is open; but if the secondary circuit is closed there will be currents, the strength of which will depend also upon the resistances and upon the counter electromotive-forces (if any) in this circuit. But these secondary currents, as they circulate around the convolutions of the secondary coil, exercise a magnetizing (or rather a demagnetizing) action, the effect of which on the core will depend not simply upon their strength, but also upon their phase. When the transformer is doing full work, the secondary current is rising in the positive sense, almost exactly as the primary is rising in the negative direction, their phases being almost exactly in opposition. That is to say, at full work the secondary currents will exercise a great demagnetizing action. The total magnetizing force[1] at work is equal to $4 \pi \, (S_1 \, i_1 + S_2 \, i_2) \div 10$, where the proper signs + and – must be assigned to i_1 and i_2 according to the sense in which they circulate around the core. Further, there will be a coefficient of self-induction L_2 in the secondary circuit, such that

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[1] See p. 176.

$$L_2 = 4\,\pi\,S_2^2 A\,\mu/l.$$

As will be seen later, there is an inter-action between the primary and secondary circuits, owing to mutual induction, tending to neutralize the effects of self-induction in both circuits.

In a well-built transformer it is clear that

$$M = \sqrt{L_1\ L_2}\,.$$

If, however, all the magnetic lines due to one circuit are not enclosed by the other, M will have a less value than is indicated by the above relation.

The relation between the two electromotive-forces and the two sets of windings is readily stated in a way sufficiently accurate for ordinary purposes, by saying that the ratio of the two electromotive-forces is equal to that of the windings, or

$$\frac{E_1}{E_2} = \frac{S_1}{S_2} = p.$$

The number p which represents the ratio of the windings we shall call the *coefficient of transformation.*

If it is assumed that there are equal weights of copper used in the primary and secondary coils, then the following relations will hold good :—

	Primary.	Secondary.	Ratio.
Windings	S_1	S_2	p
Resistance	r_1	r_2	p^2
Self-induction	L_1	L_2	p^2
Electromotive-force	E_1	E_2	p
Current	i_1	i_2	p^{-1}
Heat-waste	$i_1^2\,r_1$	$i_2^2\,r_2$	1

Also $$M = \frac{L_1}{p} = p\,L_2.$$

It must be always remembered that the symbol E is used above for the virtual or square-root-of-mean-square value of the alternating electromotive-force: the actual value of E at any moment being represented by the expression $E = D \sin 2 \pi n t$; where D is the maximum value to which E rises, and is equal to $2 \pi n$ S N (see p. 626), n being the number of alternations per second. Further, for alternate-currents (see p. 629) Ohm's law must be written as

$$i = \frac{D \sin (2 \pi n t - \phi)}{\sqrt{R^2 + 4 \pi^2 n^2 L^2}}.$$

We are now able to find a more exact expression for the induced electromotive-force in the secondary circuit, for the number of magnetic lines induced by the primary circuit into the core (when there is no current in the secondary) is M i; and therefore

$$E_2 = - M \frac{d i}{d t} = M \frac{2 \pi n D \sin \left(2 \pi n t - \phi - \frac{\pi}{2}\right)}{\sqrt{r_1^2 + 4 \pi^2 n^2 L_1^2}};$$

or, writing $2 \pi n = \omega$, we have (neglecting phase, and considering magnitude only)

$$E_2 = \frac{\omega M}{\sqrt{r_1^2 + \omega^2 L_1^2}} E_1;$$

or, putting

$$\frac{\omega M}{\sqrt{r_1^2 + \omega^2 L_1^2}} = k,$$

$$E_2 = k E_1.$$

Examining the expression k, it will be seen that if r_1 is small compared with ωL_1, as will be the case where there are very rapid alternations and plenty of iron in the core, k will be equal to M/L_1, or will be the reciprocal of p, and equal to S_2/S_1.

By leaving out of consideration differences of phase in the above argument, it must not be supposed that these differences of phase are small. On the contrary, they may be very large. If, however, assuming E_1 to be a sine-function, we remember that the average value of the square of the sine (between 0° and 360°) is equal to $\frac{1}{2}$, then we shall have the virtual primary volts E_1 equal to D divided by $\sqrt{2}$. It is in this sense (namely, taking the square-root of mean square as the basis for comparison) that we may say that E_2 is to E_1 in the same ratio as S_2 to S_1, or that the ratio of the primary and secondary volts is equal to the ratio of the primary and secondary windings. If the two windings are properly wound over the core so that there is no magnetic leakage, then the variations of magnetism of the core will set up in the two windings electromotive-forces that are precisely proportional to the respective number of turns. In the primary winding this electromotive-force will oppose that which is supplied from without. If, following the notation used for motors, we call $\mathcal{E}_1$ the volts supplied to the primary terminals, $\mathcal{E}_1$ will be greater than E_1 by an amount dependent on the internal resistance and current in the primary. Similarly, the volts at the secondary terminals e_2 will be less than E_2 by an amount dependent on the internal resistance of the secondary winding and on the secondary current. In any case, the work given out (per second) by the secondary will be very nearly equal to the work imparted to the primary; the difference being the loss due to the production of eddy-currents, and the waste work spent in carrying the residual magnetization of the iron through repeated cycles of alternation. If $\mathcal{E}_1 i_1$ be the watts imparted to the primary, and $e_2 i_2$ those given out by the secondary, it is found that $e_2 i_2$ may be as much as 97 per cent. of $\mathcal{E}_1 i_1$. A current of 10 amperes at 2000 volts imparted to a good transformer, having twenty times as many turns on its primary as it has on its secondary coil, will be transformed by the secondary into a current of 200 amperes[1] at very nearly 100 volts.

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[1] It must be remembered by beginners that the gain in quantity of current is balanced by the diminution in electromotive-force; otherwise the work would not be equal. It is a curious fact in the history of invention that in 1883 the United States Patent Office refused to grant a transformer patent to Mr. Bernstein on the ground that he could not possibly get a

One of the most difficult points for beginners to comprehend in the action of transformers is the way in which, when used in parallel distribution, they of themselves adjust the amount of primary current that flows through them from the mains. Suppose a transformer, having a primary coil of many turns of fine wire to receive a current of 1 ampere from mains at, say, 2000 volts, and having a secondary coil adapted to give out a current of 20 amperes at 100 volts. This would supply 40 lamps, each taking a ½-ampere of current. When all the lamps are on, the 20-ampere flows through the secondary, and the 1-ampere flows through the primary. If now half the lamps are turned out, only 10 amperes will be supplied by the secondary, and now only half an ampere is wanted from the mains to flow through the primary. As a matter of fact, under these circumstances, the current supplied through the primary automatically diminishes in the proper proportion. As lamp after lamp is turned out in the secondary circuit, so, little by little, the primary current also diminishes; when all lamps are out, and the secondary circuit is completely opened the primary current is found to have of itself all but stopped, although the mains are still supplied at full pressure. Nothing has been done to the primary circuit: there is still a perfect path through which the current might flow, no resistance has been inserted in the primary coil, yet the current does not flow to any extent through it. The clue to the matter lies in the inductive reaction of the iron core. As the waves of primary current circulate around the core, they set up periodic magnetizations in the iron; but the periodic fluctuations of the magnetism of the iron necessarily set up electromotive-forces in the surrounding coils. If in a short time $d\,t$, the change that takes place in the number of magnetic lines in the core is $d\,\mathrm{N}$, then during that short time the electromotive-force induced in the wire which is coiled S times round the core will be equal to $\frac{d\,\mathrm{N}}{d\,t}$ (this number should be divided by 10^8 to bring to volts). The electromotive-force in the secondary

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larger quantity of current out of the secondary than was supplied to the primary. Nevertheless, the same Patent Office in 1886 issued a patent to Gaulard and Gibbs for this very thing!

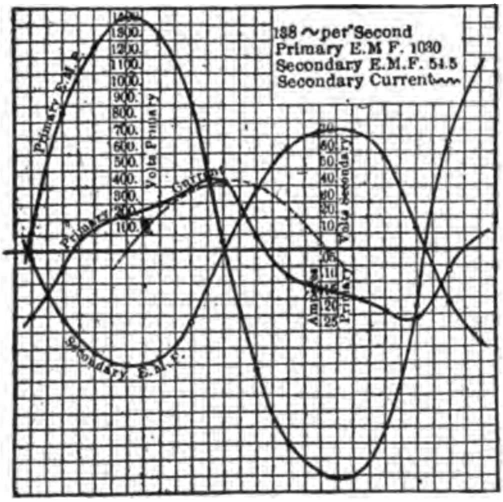
coil will be $S_2 \frac{dN}{dt}$; and there will of course be also another electromotive-force induced in the primary equal to $S_1 \frac{dN}{dt}$. Now it is this self-induced counter electromotive-force in the primary which dams back the currents from the mains when the secondary circuit is open. The variation of the magnetism of the core always tends to set up electromotive-forces opposing change. It does this in two ways. If there is no secondary it sets up back electromotive-forces in the primary which dam back the current. If there is a secondary wire present it sets up currents in the secondary in a sense opposite to those of the primary. Consider what happens when there are no lamps on: the secondary circuit is entirely idle, and takes no part in the action. The alternating electromotive-force of the mains impresses alternating currents in the primary coil, which in turn impress an alternating magnetization on the core, and this finally induces alternating electromotive-forces into the primary circuit, tending to stop the primary currents. The greater the variation of magnetization of the core, the greater the induced electromotive-force. Now consider what happens when the lamps are on. There will be considerable currents in the secondary: these are always in almost exactly opposite phase to the primary currents. When the primary current is increasing, the secondary current is increasing negatively, that is to say, is increasing whilst circulating round the core in the opposite sense to the primary. The magnetizing tendency is of course proportional to the difference between the ampere-turns of the primary and those of the secondary. [It is, as previously stated, equal to $4\pi (S_1 i_1 + S_2 i_2) \div 10$, the proper signs being assigned to the currents according to their sense.] If, as is the usual case, the secondary volts are maintained nearly constant, it follows that the cycles of magnetization, and therefore the nett magnetizing forces, are nearly the same at all loads. It would therefore appear as though the back electromotive-force tending to dam back the primary current ought to be the same at all loads. But this we know is not true. The explanation lies in the phase-relations: for, at light loads the counter electromotive-force in the primary is almost exactly in opposite phase to the primary impressed electromotive-force, whilst at full load it is nearly in quadrature with the latter. To put it into other words, as lamps are turned on in the secondary and more secondary current flows, the increased mutual induction virtually wipes out the self-induction in the primary circuit, and the effective back electromotive-forces in the primary coil, which in the first case dammed back the current from the mains, are less; hence more current flows in the primary.

Graphic constructions illustrating the variations of phase and magnitude of the electromotive-forces and currents have been given by Kapp, Blakesley, and Fleming. If the impressed E_1 is constant, then the magnetization is of course carried to the greatest degree when the transformer is working on open circuit. If, however, the system is so regulated or over-compounded as to keep up a constant pressure at the lamps, then the magnetization of the cores is a maximum at full load. It is expedient to arrange that there shall be so much iron in the core that the induction in it need never be carried above 6000 or 7000 lines to the square centimetre. It is possible to work above these values, but the transformer emits a singing noise, and the iron grows hot. Work is, of course, spent in carrying the iron to a high degree of magnetization. Of this work, the greater part is returned to the secondary circuit during the next part of the cycle as the magnetization of the iron descends; but part, namely, that spent in producing the so-called permanent portion of the magnetization, is lost, being frittered down into heat. As to the phases of the various waves, as mentioned above, the secondary current is always in almost exactly opposite phase to the primary current; and the secondary electromotive-force is in almost exactly opposite phase to the primary electromotive-force. But the difference of phase between E_1 and i_1 varies greatly with the work done. When there are no lamps on, and no secondary current, i_1 is small, and its phase differs by very nearly 90° from that of E_1: as lamps are switched on and i_2 grows, i_1 grows also, and the angle of lag between E_1

and i_1 grows less. The phase of the magnetization of the core (which is always necessarily 90° in advance of the phase of E_2) is always[1] very nearly 90° behind the phase of E_1.

The actual performance of transformers has been carefully examined by Prof. H. J. Ryan,[2] who has plotted out curves to show the forms and phases of the several varying quantities. The transformer used was a small one of 600 watts capacity adapted for transforming down from 1000. to 50 volts, the number of windings being 675 in the primary, and 35 in the secondary coil. The volume of laminated iron was about 2050 cubic cm. The mean length of the magnetic circuit was 30·8 cm. and mean cross section 63·3 sq. cm.; the frequency used was 138. Figs. 468, 469, and 470 show the results. It will be noted that although the primary

Fig. 468:



Transformer Curves on Open Circuit.

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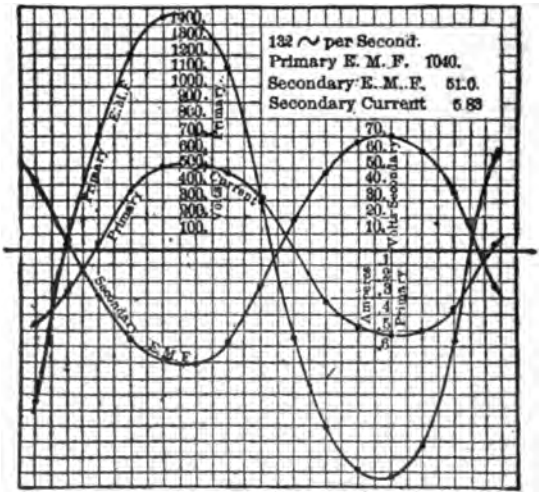
[1] See experiments by Major Cardew, in *Electrical Engineer*, July. 1887, p. 358.

[2] *Amer. Inst. Electrical Engineers*, 1889 and 1890. See also *Electrical World*, xiv. 419, Dec. 28, 1889, and xvi. 10, July 25, 1890; also *The Electrician*, xxiv. 263, and xxv. 313, 1890; also *La Lumière Electrique*, xxxv. 233, 1890. See also an appendix paper by Messrs. Humphrey and Powell in *Electrical World*, xvi. 11, 1890, and *The Electrician*, xxv. 280, 1890.

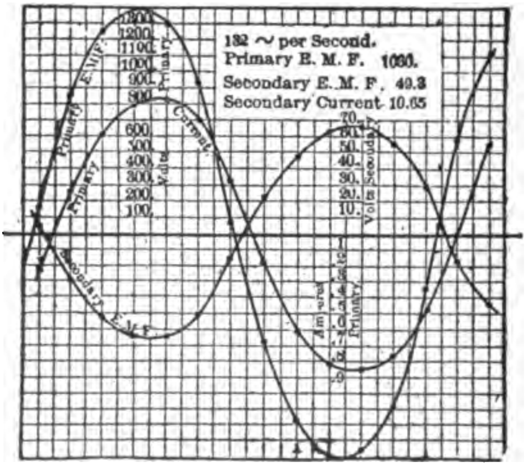
current curve differs widely from a curve of sines (especially at light loads), nevertheless the curve of secondary volts is

FIG. 469.



TRANSFORMER CURVES AT HALF LOAD.

FIG. 470.



TRANSFORMER CURVES AT FULL LOAD.

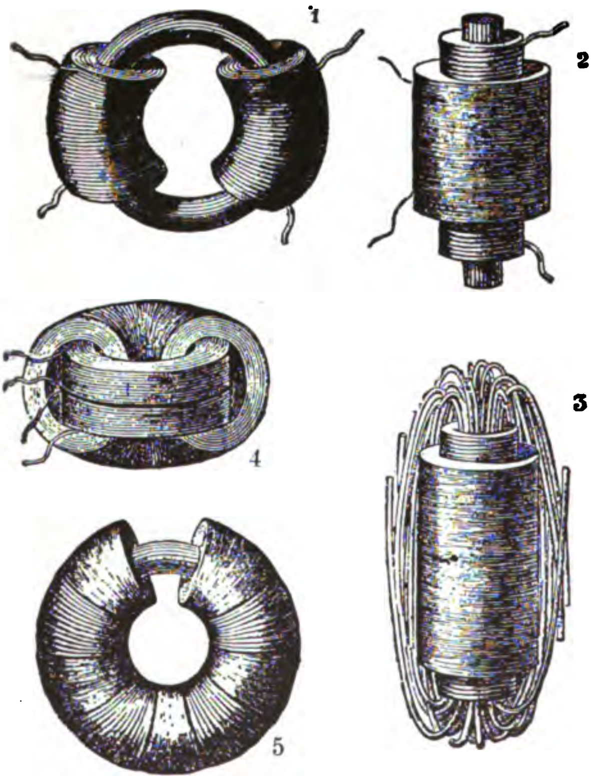
much more nearly like a sine-curve; and it is always in almost exact opposition of phase to the curve of primary volts. In

Ryan's paper are many valuable remarks, not the least important being a passage in which he points out that leakage of magnetism not only diminishes the mutual induction, but increases the self-induction of each circuit, and therefore tends to cause a lag in both the currents. In a second paper, Prof. Ryan shows that the loss of energy by eddy-currents in the core is less when the core is hot than when it is cold.

CONSTRUCTION OF ALTERNATING TRANSFORMERS.

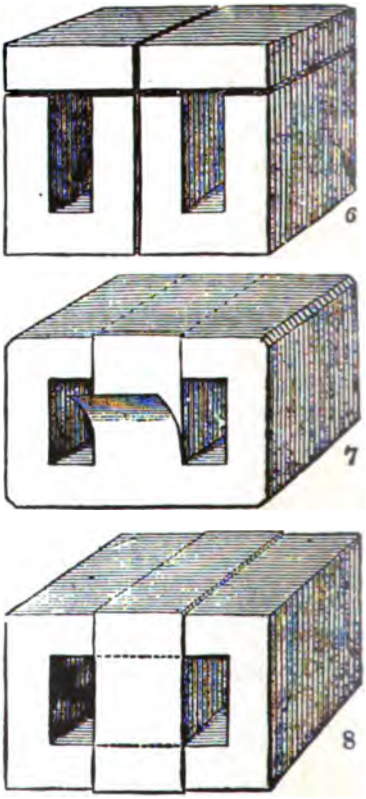
All transformers consist of a core of iron, around which the primary and secondary coils are so wound that the core carries the magnetic lines from the one set of coils through the other. Faraday's first induction-coil, No. 1 in Fig. 471, is thoroughly typical of the principle common to all transformers. In Faraday's actual ring the iron was not laminated. No. 2 of Fig. 471 is the cylindrical type of induction-coil introduced by Masson and Ritchie, and perfected for spark purposes by Ruhmkorff. No. 3 depicts the form given to the transformer by Varley for telegraphic purposes. The core of iron wires is made long, and the ends are bent over so as to constitute practically a closed magnetic circuit. The Ferranti transformer resembles this, but has the core of narrow strips of sheet iron. A similar form has been used recently by Gaulard and Gibbs. No. 4 is a form introduced by Zipernowsky; in this the primary and secondary coils are laid upon one another, and the iron core is then wound through and over them by a shuttle, so that the whole of the copper is enclosed within the iron. In the drawing of Nos. 3 and 4 the front portion of the iron winding is represented as removed to show the interior. Mr. Kapp has proposed the name of "shell-transformers" for this type of apparatus as distinguished from those with a mere straight or a non-expanded internal core. No. 5, which is also a form due to Zipernowsky, is constructed somewhat like a Gramme ring. There is an iron wire ring core, upon which the copper coils are wound in sections, but with alternate sections connected together, one set as primary, the other as secondary. In the drawing, one of the ten sections is represented as removed to show the core. Nos. 6, 7, and 8 represent three closely allied methods of procuring the necessary structure of laminated iron, the parts in these instances being stamped from sheet iron. The copper coils are not shown in these three, but in each they consist of two sets of windings previously wound on rectangular formers of such a form as to admit of insertion into the iron stampings. In No. 6, which shows the method of Kapp and Snell, there are two sets of U-shaped stampings, set side by side, forming two parallel channels to receive the coils. The stampings that

Fig. 471.



VARIOUS TYPES OF ALTERNATING TRANSFORMERS.

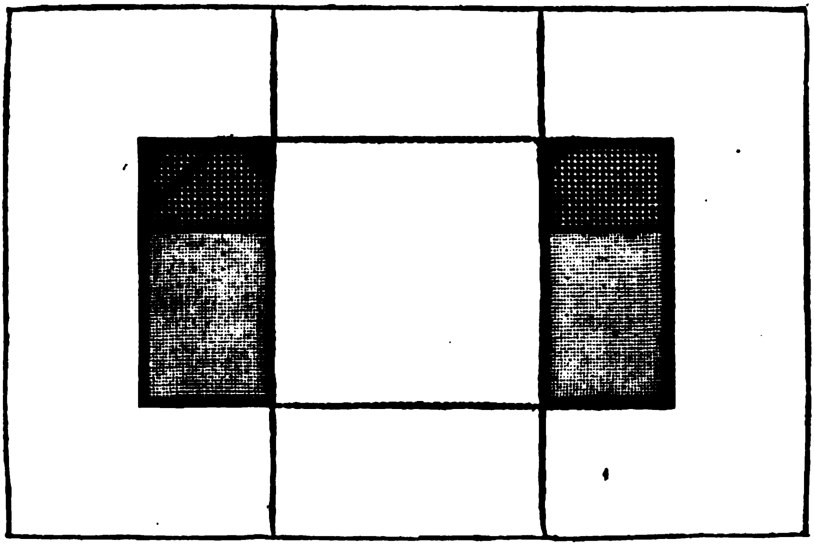
Fig 472.



CORE-PLATES OF TRANSFORMERS.

are removed between the limits of the U pieces serve to complete the magnetic circuits above. No. 7 is the form adopted by Westinghouse. The stamping in this form must be bent up in order to slip it on over the coils; the core being put together over the coils. With Mordey's form, No. 8, the piece which is removed from the interior of the rectangular stamping is placed across it (after having been covered on one side with paper as insulation), the outer rectangular stampings being passed over the outside of the coils, and the cross-pieces slipped in between them, thus avoiding waste of material, and securing a good magnetic circuit with ample ventilation. Fig. 473 shows the exact proportions of the stampings of Mordey's transformer, including a section of the coils. The newest form of this apparatus, which is constructed by the Brush (Anglo-American) Company, is further depicted in Figs. 474, 475.

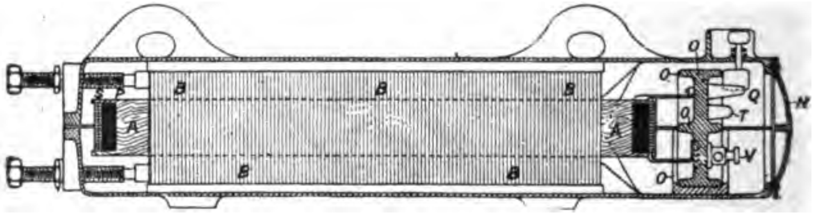
FIG. 473.



MORDEY'S TRANSFORMER (Section).

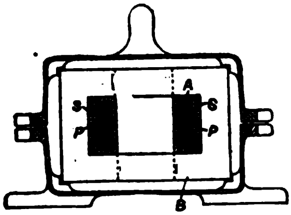
As an example, the following dimensions are given for a transformer capable of transforming a current of 1·5 ampere at 1000 volts down to a current of 37·5 amperes at 40 volts. Total external size, 20 × 6 × 4 inches; $S_1 = 300$; $S_2 = 12$; $r_1 = 10$ ohms; $r_2 = 0·014$ ohms; gauge of primary wire, 0·035inch; secondary wire 25 in parallel, each 0·12 inch gauge; weight of copper in coils, about 5 lbs. in primary and 5½ lbs. in secondary; weight of iron used, about 50 lbs.; efficiency, 97·2 per cent.

Fig. 474



Mordey's Transformer (Section).

Fig. 475.



Mordey's Transformer (Transverse section).

In this pattern the coils P and S are wound upon a light former A, made of hard wood steeped in ozokerit. The core-disks B are partly made of stampings resembling Fig. 473, interlaced, and partly of other stampings which fill up the interstices which would otherwise be left between the superposed pieces. By this means the leakage of the magnetic circuit is reduced to a negligible amount. The whole is secured in a cast-iron cover made water-tight by a packing of rubber. The connexions, switch, and safety-fuses are mounted on a porcelain block O, in the end of the chamber.

Fig. 476 illustrates the so-called "hedgehog" transformer of Swinburne,[1] having as core a bundle of iron wires which, after receiving the copper coils, are spread out at their ends so as to reduce the magnetic reluctance, which is in any case great, the magnetic circuit being an open one.

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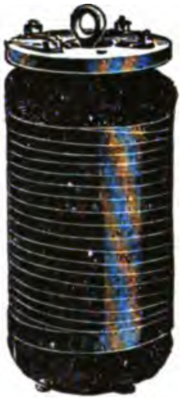
[1] *Journal Inst. Electr. Engineers*, xx. 183, 1891.

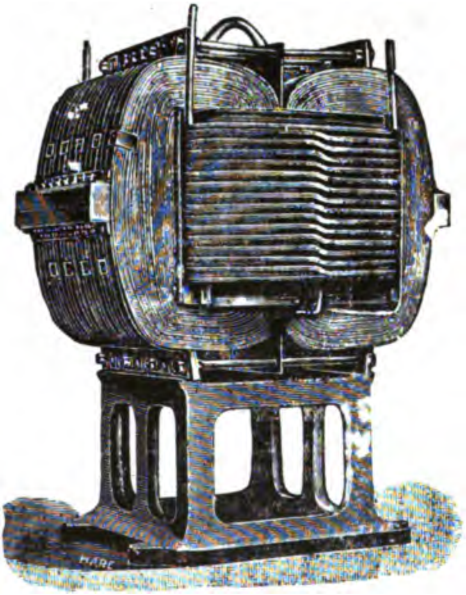
Ferranti's transformer (Fig. 477) for extra high pressure work has a core made of a large number of thin strips of iron, which pass vertically up through the middle of the copper coils, and are bent round below and above on each side and interlapped so as to complete the magnetic circuit. The coils are made of copper-strip, very carefully insulated, and compacted together in sections by insulating material. There are three coils thus built up, the innermost being a portion of the primary, outside this the secondary, and outside this again the rest of the primary. Sheets of ebonite are interposed in the spaces between these coils so as to prevent sparking across from the high-pressure coils. There is also room for air ventilation in the vertical spaces where these sheets of ebonite are wrapped round between the three piles of coils.

Fig. 476.



Swinburne's Hedgehog Transformer.

Fig. 477.



Ferranti's Transformer.

With most of the preceding modes of construction the coils cannot be readily removed from the transformer, owing to the mode of putting together the iron parts. A more accessible structure is that designed by C. E. L. Brown, in which the coils are wound on a cylindrical tube of insulating material through which can be inserted a core made up of laminæ of different widths, almost filling the tube, and projecting squarely at its ends. The magnetic circuit is completed by means of U-shaped iron stampings assembled in two sets, one placed below, and the other above, which can be removed *en bloc*, so giving access to the coils. These transformers are immersed in oil.

Another construction, which also gives ready access to the coils, is the design of Mr. Kapp depicted in Plate XXIX. Here the coils, primary and secondary, are wound on ebonite bobbins, which slip over a long rectangular core made up of plates. To complete the magnetic circuit other assemblages of core plates of equal length are carried parallel to the core, above and below, and the four spaces at the ends are filled by four blocks of small stampings assembled together. The whole is secured in a substantial frame and protected by an external cover of cast iron bolted down.

The advantages possessed by transformers which have closed magnetic circuits over those which have not are of various kinds; in particular they require a smaller exciting current for an equal magnetic cycle, so that there is less waste of energy in the copper, particularly on small loads. On the other hand, in the open-circuit transformers, owing to the self-demagnetizing action of non-closed iron cores, there is less waste of energy by hysteresis in the iron. This point has been strongly insisted on by Mr. Swinburne.[1] Some experiments made by Mr. Ferranti are suggestive. A number of iron strips were placed side by side and a coil wound upon them, the ends of the strips protruding far beyond the coil. This was used as a self-induction or choking coil at 100 volts, alternating at 66 periods per second: the number of watts expended by the current being a measure of the work required to carry the iron through the magnetic cycle needful to balance the impressed volts. When the strips were simply straight, the current was found to be 22 amperes, giving apparent watts 2200; but as the angle of lag was about 86° 30′, the true watts were only 135·5. Then the ends of the strips were spread out to imitate the hedgehog arrangement, with the result that to carry the iron core through the same magnetic cycle as before (or a slightly greater cycle) required only 10·75 amperes, with expenditure of 1075 apparent or 116·9 real watts. Lastly, when the ends of the strips were bent right round and laid between one another, completing the magnetic circuit as in the Ferranti transformer, the current fell to 0·9 ampere, indicating that a still higher degree of magnetization had been obtained with expenditure of only 90 apparent or 49·6 real watts.

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[1] Proc. British Association, 1889 (see *The Electrician*). See also an important series of articles by Mr. Sydney Evershed, on Design of Transformers in *The Electrician*, beginning vol. xxvi., p. 477.

Another point strongly in favour of closed circuit transformers is the entire absence of waste from eddy-currents in the copper conductors, however massive; for the magnetic lines seem to snap across them absolutely instantaneously, so that there is never any difference in the intensity of the magnetic field in which the two sides of a conductor find themselves.

The relative advantages of open and closed circuit transformers have been lately discussed in the Institution of Electrical Engineers.[1]

Tests of the efficiency of transformers have been given by Mordey,[2] Ayrton,[3] and others.

For further information on the constructional details of transformers the reader is referred to a series of articles by R. Kennedy, in the *Electrical Review*, xx. 247 et seq., 1887, since republished in separate form under the title *Electrical Distribution by Alternating Currents and Transformers;* to an article by Rechniewski, in *La Lumière Electrique*, xxvi. 95, 1887; to the paper by G. Kapp, in *Journal Soc. Teleg. Engineers*, xvii. 96, 1888, to which reference is made above; to the papers by Mr. Swinburne and by Mr. Evershed already alluded to; and to the volumes of Prof. Fleming on *The Alternate Current Transformer*, which appeared in serial form in *The Electrician* in the years 1889–91.

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[1] See *Journal Inst. Electrical Engineers*, xx. 183 to 251, 1891.

[2] *Ib.*, xviii. 609, 1890.

[3] *Ib.*, 664.

THEORY OF ALTERNATE TRANSFORMERS.

There are two ways of treating the theory of transformers—the first by introducing the notion of coefficients of mutual and self-induction into the differential equations for the two circuits the second by considering the magnetomotive-forces at work in the iron core as the result of the algebraic sum of the ampere-turns in the two circuits, and deducing the electromotive-forces which result from the variations in the magnetic induction of the core—

First Method.

This method, introduced by Maxwell,[1] consists in finding the electromotive-force induced in the second circuit by the variations of current impressed upon the first circuit. Accordingly we write as the differential equation of the first circuit—

$$E_1 - M \frac{d\,i_2}{d\,t} - L_1 \frac{d\,i_1}{d\,t} - R_1 i_1 = 0 ; \qquad (1)$$

where E_1 is the impressed electromotive-force of the dynamo, which is supposed to fulfil the condition $E_1 = D \sin 2 \pi n t$ (see p. 626), and where L_1 and R_1 are the coefficient of self-induction and resistance of the primary circuit. If the supposition is admitted that a constant (alternating) potential can be maintained at the terminals of the primary coil (by proper compounding of the dynamo, see p. 747, or otherwise), then the letters E_1, L_1, and R_1, may be taken to apply to that part of the primary circuit only which lies between the terminals of the primary coil. From this differential equation we have to deduce a value for $M \frac{d\,i_1}{d\,t}$. For brevity we will write ω for $2 \pi n$; and $- \omega^2 i$ for $\frac{d^2 i}{d\,t^2}$, because i is a sine-function. Then differentiating equation (1) we get—

$$\frac{d\,E_1}{d\,t} + M\,\omega^2 i_2 + L_1\,\omega^2 i_1 - R_1 \frac{d\,i_1}{d\,t} = 0. \qquad (2)$$

---

[1] *Philosophical Transactions*, clv. pt. i. p. 459, 1865. In this paper Maxwell shows that the effect of the second circuit is to add to the apparent resistance and diminish the apparent self-induction of the first circuit. The student will find the equations more fully treated by Mascart and Joubert, *Electricité et Magnétisme*, i. 593, and ii. 834; also by Hopkinson, *Journal Soc. Teleg. Engineers*, xiii. 511, 1884; Ferraris, *Mem. Accad. Sci.* (Turin), xxxvii. 1885; and by Vaschy, *Annales Télégraphiques*, 1885–6, or *Théorie des Machines Magnéto et Dynamo-électriques*, p. 31. A summary of Maxwell's work is given in Fleming's book.

Now multiply this by R_1 to get equation (3), and multiply equation (1) by $L_1 \omega^2$, to get equation (4); and add (3) and (4) to get (5).

$$R_1 \frac{dE_1}{dt} + M \omega^2 R_1 i_2 + L_1 \omega^2 R_1 i_1 - R_1^2 \frac{d i_1}{d t} = 0, \qquad (3)$$

$$L_1 \omega^2 E_1 - L_1 \omega^2 M \frac{d i_2}{dt} - L_1^2 \omega^2 \frac{d i_1}{dt} - L_1 \omega^2 R_1 i_1 = 0, \qquad (4)$$

$$\left(R_1^2 + L_1^2 \omega^2\right) \frac{d i_1}{d t} = R_1 \frac{dE_1}{dt} + L_1 \omega^2 E_1 + M \omega^2 \left(R_1 i_2 - L_1 \frac{d i_2}{dt}\right). \qquad (5)$$

Now multiply every term by $\frac{M}{R_1^2 + L_1^2 \omega^2}$, and write the following abbreviations:—

$$\frac{M \omega}{\sqrt{R_1^2 + L_1^2 \omega^2}} = k,$$

$$k^2 R_1 = \rho,$$

$$k^2 L_1 = \lambda,$$

$-\frac{k^2}{M}\left(\frac{R_1}{\omega_2} \cdot \frac{dE_1}{d t} + L_1 E_1\right) = E_2 = k E_1 \sin(\omega t - \phi)$, where ϕ relates to the phase of the electromotive-force; and we may write equation (5) as—

$$M \frac{d i_1}{d t} = \rho i_2 - \lambda \frac{d i_2}{d t} - E_2. \qquad (6)$$

Now the differential equation for the second circuit is—

$$M \frac{d i_1}{d t} + L_2 \frac{d i_2}{d t} + R_2 i_2 = 0; \qquad (7)$$

there being in this circuit no other electromotive-forces than those due to mutual and self-induction. Inserting in (7) the value obtained in (6), we get as the final equation—

$$(R_2 + \rho) i_2 + (L_2 - \lambda) \frac{d i_2}{d t} - E_2 = 0. \qquad (8)$$

This shows us that the whole effect is equivalent to that which would happen if, the primary circuit being absent, there were introduced into the secondary circuit an electromotive-force equal to $k E_1$, and at the same time the resistance were increased by a quantity equal to $k^2 R_1$, and the self-induction were diminished by a quantity equal to $k_2 L_1$. Further, examination of k shows us that if the frequency of alternation and the permeability of the iron core be great enough, k becomes equal to $M \div L_1$, or equal to the reciprocal of p, the ratio of the primary and second windings. But if there are equal weights of copper in the two coils, $L_1 = p^2 L_2$ and $R_1 = p^2 R_2$. So that the effect, when the transformer is fully at work, is to make $\lambda = L_2$, and $\rho =$ the resistance of the secondary coil; or self-induction is wiped out, and the internal resistance of the secondary is virtually doubled.

Second Method.

In this method, due to Hopkinson,[1] we begin by considering the magnetomotive-force requisite to force N magnetic lines through a core having length l and permeability μ. This magnetomotive-force is due to the algebraic sum of the ampere-turns in the two coils. Following the argument on p. 177, Chapter VI., we may therefore write :—

$$\frac{4\pi}{10}\Big(S_1 i_1 + S_2 i_2\Big) \div \frac{l}{A\mu} = N; \qquad (1)$$

or if the core has area of cross-section A, and there are B lines to the square centimetre, we may write $N = A\,B$; and then, the magnetomotive-force will be—

$$\frac{4\pi}{10}\Big(S_1 i_1 + S_2 i_2\Big) = A\,B\,\frac{l}{A\mu} = \frac{B}{\mu}\,l = H\,l. \qquad (2)$$

We then write two equations for the electromotive-forces impressed in the two circuits as follows :—

$$\left\{\begin{aligned} E_1 &= R_1 i_1 - S_1 \frac{dN}{dt} = R_1 i_1 - S_1 A \frac{dB}{dt}, && (3)\\ 0 &= \Big(r_2 + R_2\Big) i_2 - S_2 \frac{dN}{dt} = \Big(r_2 + R_2\Big) i_2 - S_2 A \frac{dB}{dt}; && (4)\end{aligned}\right.$$

where R_2 is the resistance of the lamp circuit, and r_2 the internal resistance of the secondary coil. Multiplying (3) by S_2 and (4) by S_1, we deduce—

$$S_2 E_1 = S_2 R_1 i_1 - S_1 (r_2 + R_2) i_2;$$

which with equation (2) gives—

$$i_1 \left\{ S_2^2 R_1 + S_1^2 (r_2 + R_2) \right\} = S_2^2 E_1 + S_1 (r_2 + R_2)(10\,H\,l \div 4\pi),$$

$$i_2 \left\{ S_2^2 R_1 + S_1^2 (r_2 + R_2) \right\} = - S_1 S_2 E_1 + S_2 R_1 (10\,H\,l \div 4\pi);$$

and

$$A\frac{dB}{dt} = - \frac{(r_2 + R_2) S_1 E_1}{S_2^2 R_1 + S_1^2 (r_2 + R_2)} + \frac{10\,H\,l}{4\pi} \cdot \frac{R_1 (r_2 + R_2)}{S_2^2 R_1 + S_1^2 (r_2 + R_2)}. \quad (5)$$

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[1] *Proc. Roy. Soc.*, February 1887.

The second term may be neglected simply because $H\,l$ is small compared with $\frac{4\pi}{10} S_1\, i_1$; in other words, because it is only the difference between $S_1\, i_1$ and $S_2\, i_2$ (both of which are very large), that is needed as a magnetomotive-force, and this is small if the permeability of the iron is great as it is when, as in actual practice, B is not carried above 8000 or 10,000 lines to the square centimetre. We have then—

$$A\frac{dB}{dt} = \frac{dN}{dt} = -\frac{(r_2 + R_2)\, S_1\, E_1}{S_2^2\, R_1 + S_1^2\, (r_2 + R_2)}.$$

And remembering that $E_2 = S_2\,\frac{dN}{dt}$, we get

$$E_2 = -\frac{(r_2 + R_2)\, E_1\, \frac{S_2}{S_1}}{\frac{S_2^2}{S_1^2} R_1 + r_2 + R_2}.$$

But E_2, the effective electromotive force in the secondary circuit, is equal to $(r_2 + R_2)\, i_2$; hence it follows that—

$$i^2 = -\frac{E_1\, \frac{S_2}{S_1}}{\frac{S_2^2}{S_1^2} R_1 + r_2 + R_2}. \qquad (6)$$

Now if the condition of supply in the mains is such as to give constant-potential at the terminals of the primary circuit, we may take E_1 and R_1 as referring to that which is internal to the primary coil; and it is evident that the effect of the transformer is to reduce the volts in proportion to the ratio of the windings, and to add to the resistance of the secondary circuit a term equal to the resistance of the primary circuit reduced in proportion to the square of the ratio of the windings. It also follows, from the negative sign in (6), that the two currents are in exactly opposite phases.

An important study of the theory of transformers has been made by Prof. Perry,[1] who finds several important results. If it be assumed that there is no magnetic leakage and that there are no magnetic reactions in the outer secondary circuit, then, though the lag of primary current behind the impressed primary voltage varies considerably at different loads, yet the lag of the secondary current behind the impressed primary voltage is always nearly 180°; and, whatever the *form* of the impressed primary curve of volts, the resultant curve of secondary amperes is of the same form. But if there is even a small amount of leakage—as little as 1·33 per cent. of the magnetic flux—these conclusions must be modified, the secondary current being now not nearly exactly in opposite phase to the primary voltage, though almost exactly in opposite phase to the primary current, the lag of which depends *inter alia* on the coefficient of leakage.

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[1] *Philosophical Magazine*, August 1891.

Professor Perry has lately further investigated the theory of a transformer wound with any number of separate circuits. Of this investigation, which is otherwise unpublished, the following are the chief points.

Let E_1, E_2, E_3 .... &c., be the independent impressed volts in the various circuits. Assume that there is no magnetic leakage. Let the ampere-turns be written

$$A = S_1\, i_1 + S_2\, i_2 + \ldots\ldots S_x i_x.$$

Let the permeance of the core be written

$$\sigma = \frac{a\mu}{l}\, 4\, \pi \div 10,$$

where a is the cross-section and l the length of the core. It is assumed that μ is a constant for a given cycle.

Let the symbol θ stand for the operator $\frac{d}{d\,t}$. The numerical value of this operator will be in practice a quantity of the order of magnitude 600; for, assuming the alternations n to be about 100 per second, and that the magnetization of the core follows approximately a sine-function of the time, it results that the induced electromotive-forces will be also sine-functions differing $\frac{\pi}{2}$ in phase: for

$$\frac{d\,(\sin 2\,\pi\, n\, t)}{d\,t} = 2\,\pi\, n \cos 2\,\pi\, n\, t = 2\,\pi\, n\, \left(\sin 2\,\pi\, n\, t - \frac{\pi}{2}\right).$$

Whence $\frac{d}{d\,t} = 2\,\pi\, n$, or is numerically 628.

Then in any circuit the current sent through its resistance will depend only on the impressed volts in that circuit (if any) and the volts due to the inductive action of the core. There is no need to divide the latter arbitrarily into separate parts, a self-inductive part and parts due to mutual inductions with each of the other circuits.

Hence we may at once write :—

$$\begin{aligned} E_1 &= R_1 i_1 + S_1 \sigma \theta A, \\ E_2 &= R_2 i_2 + S_2 \sigma \theta A, \\ E_3 &= \ldots\ldots \\ &\ldots\ldots\ldots \\ E_x &= R_x i_x + S_x \sigma \theta A. \end{aligned}$$

There being as many equations as circuits. Now multiply each equation severally by $\frac{S_1}{R_1}, \frac{S_2}{R_2}$, &c. . . . .; and add them together, giving:—

$$\Sigma \frac{S}{R} E = A + q \sigma \theta A,$$

$$\text{where } q = \frac{S_1^2}{R_1} + \frac{S_2^2}{R_2} + \ldots\ldots + \frac{S_x^2}{R_x}.$$

In this quantity q the important term for actual work is the first, because in all the other terms the R part is relatively large, owing to the presence of external resistances, unless any of the circuits are short-circuited. Any closed internal circuit in which eddy-currents might occur may be treated as a term in this series, and might not be negligible in comparison with the first term. Now writing the symbol -1 as the exponent of an inverse operation, we have for the value, at any instant, of the total ampere-turns :—

$$A = (1 + q \sigma \theta)^{-1} \Sigma \frac{S}{R} E.$$

Inserting this in any of the equations, and taking as typical of the lot the pth circuit, we get for the current in the pth circuit,

$$i_p = \frac{E_p}{R_p} - \frac{S_p}{R_p} (1 + q \sigma \theta)^{-1} \sigma \theta \Sigma \frac{S}{R} E.$$

We have thus got an expression for the current in any circuit, whatever the electromotive-forces or resistances in any of the circuits.

To apply this to the ordinary case of a transformer having but one primary circuit, we have merely to write E_2, E_3, &c., $= 0$. And for convenience we will consider R_1 as the internal resistance only, so that we may replace E_1 by V the volts at the primary terminals. We still retain the possibility of any number of secondary or induced circuits. We then have:

$$A = \frac{S_1}{R_1}(1 + q\sigma\theta)^{-1} V \quad . \; . \; . \; . \; . \; . \quad (1)$$

$$i_1 = \frac{R_1}{V} - \frac{S_1^2}{R_1}\frac{\sigma\theta}{1 + q\sigma\theta} V \quad . \; . \; . \; . \; . \quad (2)$$

$$i_p = 0 - \frac{S_p S_1}{R_p R_1}\frac{\sigma\theta}{1 + q\sigma\theta} V \quad . \; . \; . \; . \; . \; . \quad (3)$$

Now since in practice $\theta \gtreqless 600$, $q\delta\theta$ is large compared with 1. Hence the last results reduced to

$$A = \frac{S_1}{R_1 q\sigma}\int V\,dt \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1a)$$

$$i_1 = \frac{V}{R_1} - \frac{S_1^2}{R_1}\frac{V}{q} + \frac{1}{qR_1\sigma}\int V\,dt \quad . \; . \quad (2a)$$

$$i_p = -\frac{S_p S_1}{R_p R_1}\frac{V}{q} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3a)$$

If there is no load on any of the secondaries, R_2, R_3, &c., are $= \infty$, and $q = S_1^2/R_1$;

$$i_1 = \frac{1}{S_1^2\sigma}\int V\,dt \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2b)$$

or at full load

$$i_1 = \frac{V}{R_1}\left(1 - \frac{S_1^2}{q}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (2c)$$

For further discussions on alternating transformers see—

Ferraris: *La Lumière Electrique*, xvi. 399, 1885; xxvii. 518, 1888; and *Electrical Review*, xvi. 256, 343 seqq. 1885; xxii. 221, 252, 1888.

G. Kapp: *Industries*, April. 1887; and *Electrician*, 1887. Also *Journal Soc. Teleg. Engineers*, xvii. 96, 1888, with discussion thereon.

G. Forbes: *Journ. Soc. Teleg. Engineers*, xvii. 153, 1888.

Rechniewski: *La Lumière Electrique*, xxv. 613, 1887.

Peukert and Zickler: *Zeitschrift für Elektrotechnik*, 1886; and *La Lumière Electrique*, xxi. 276, 1886. Also *Electrical Review*, xix. 80, 1886.

CONSTANT-CURRENT ALTERNATING TRANSFORMERS.

Transformers arranged so that the two self-inductions of the two coils are high compared with the mutual induction between them have been designed by Elihu Thomson and by Stanley for the purpose of yielding alternating currents of a constant number of virtual amperes. Swinburne[1] has pointed out that a hedgehog transformer will answer in this way if the primary and secondary coils are wound on opposite ends instead of being wound close together. An ordinary transformer can be adapted to such service if a choking-coil is introduced into the secondary circuit. The use of constant-current apparatus is for feeding arc and glow lamps in series.

USE OF TRANSFORMERS FOR REGULATING ALTERNATORS.

By use of transformers it is possible to attain a means of self-regulation akin to the methods of compound winding adopted for continuous-current dynamos. Assuming that an initial and constant excitation can be afforded by a separate exciter, it remains to supplement this by a variable excitation which, in the case of constant-potential distribution, must be proportional to the main current, or in the case of constant-current distribution must be proportional to the resistance in the circuit. Various combinations have been suggested by Zipernowsky, Kennedy, and Schallenberger.

Fig. 478 shows Zipernowsky's arrangement, and represents diagrammatically a machine with internal revolving field-magnet of eight poles. The armature consists of eight stationary coils, seven of which are joined in series to feed the main circuit, the eighth coil S being separated from the rest and used to provide excitation for the field-magnets, its currents being conveyed in through a suitable commutator on the shaft of the machine. In the main circuit, just beyond the terminals of the machine, is inserted the primary coil of a small transformer T, the secondary of which is connected with the exciting circuit. In this way an additional excitation is procured, always proportional in amount to the currents that are flowing in the main circuit. It is possible to avoid using the coil S by substituting the secondary of another transformer, the primary of which is placed as a shunt across the mains.

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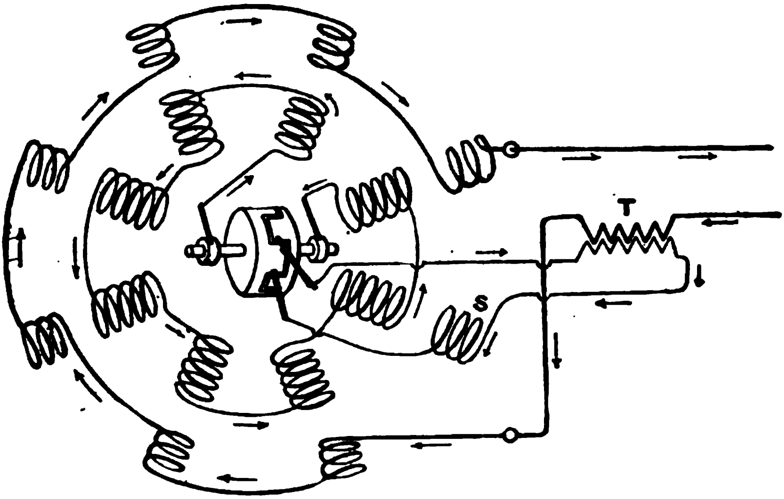
[1] *Journal Inst. Electrical Engineers*, xx. 192, 1891.

FIG. 478.



ZIPERNOWSKY'S METHOD OF COMPOUNDING ALTERNATE-CURRENT DYNAMO.

MOTOR-DYNAMOS.

These are of two sorts: (1) for transforming a continuous current at any voltage to a continuous current of different strength at a different voltage; (2) for transforming a continuous current into an alternating one, or *vice versâ.*

CONTINUOUS-CURRENT TRANSFORMERS.

Gramme, in 1874, constructed a machine with a ring-armature wound with two circuits—one of coarse wire, the other with fine wire, having eight times as many turns. Two separate commutators were connected with the two windings. This machine could be used for transforming either from high to low potential or *vice versâ*. The same end can be less conveniently attained by uniting on one shaft the armatures of two dynamos, one to be used as a motor driving the other as a generator; and these may have separate field-magnets, or a common field-magnet. In England, continuous-current transformers have been introduced with success by Messrs. Laurence, Paris, and Scott,[1] who employ a 2-pole machine with cast-iron frame and an armature wound with double circuits. There is very little sparking with such machines, as the reactions in the two sets of coils tend to correct each other. The field-magnet is excited as a shunt to the low-potential armature coil. Swinburne has discussed many possible combinations, including one for transforming from a constant current to a constant-potential condition of distribution. In the Chelsea central station a number of motor-dynamos are used. They have been described in detail by Major-General Webber,[2] and include several types, some being by Laurence and Scott, others of Elwell-Parker construction.

The following are particulars of an Elwell-Parker continuous-current transformer, closely resembling the machine drawn in Plate VI., drum wound, but having a commutator at each end of the armature.

	Primary.	Secondary.
Volts	1000	110
Amperes	40	360
Resistance of armature winding (ohms)	0·427	0·0052
Conductors around armature ..	648	72
Segments in commutator	162	36

Speed 500 revolutions per minute.
Field-magnets: shunt-wound with 3080 turns; resistance 8·5 ohms.
Armature core: diameter of disks $16\frac{5}{16}$ in.; nett cross section of iron 326 sq. in.
Efficiency of double transformation: at full load 83 per cent.; at half load 75 per cent.

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[1] See *Electrician*, xix. 517, October 1887; and *Electrical Review*, xxii. 4, 1888.

[2] *Journal Inst. Electrical Engineers*, xx. 63 to 69, 1891, giving drawings and data of three machines.

A somewhat different system of continuous-current transformation has been suggested by Cabanellas,[1] and patented by Edison,[2] in which neither armature nor field-magnet revolves, but in which, by means of a revolving commutator, the magnetic polarity of a double-wound armature is continually caused to rotate. In a further modification of this idea, due to Jehl and Rupp, a mass of iron, which completes the magnetic circuit, rotates within the double-wound ring.[3]

It has been proposed to employ a motor-dynamo to compensate the drop in voltage on long mains by inserting into the main at a distant point a series-motor driving an armature placed as a shunt across the mains. Lahmeyer[4] calls this device a "far-leading" dynamo (Fernleitungs-dynamo).

Another combination is useful for three-wire and five-wire systems of distribution, a number of armatures or windings on the same shaft being connected across the various pairs of mains. If at any pair of mains the potential drops, this armature will begin to feed this pair, being driven by the other armatures as motors. Such a device is called an "equalizing" dynamo (Ausgleichungs-dynamo).

For further notices of the methods of continuous-current transformation, the reader is referred to articles by Elihu Thomson, in *Electrical World*, x. 108, 1887; by R. P. Sellon, in *Electrician*, xx. 633, 1888; and by Rechniewski, in *La Lumière Électrique*, xxv. 416, 1887.

THEORY OF CONTINUOUS-CURRENT TRANSFORMERS.

Let E be the potential at terminals of the primary or motor part, and e that at terminals of the secondary or generator part. Let the i_1, r_1, and C_1 stand respectively for the armature current, armature resistance, and number of armature conductors of the primary part; and i_2, r_2, and C_2 for the corresponding quantities of the secondary part. Then the two induced electromotive-forces will be—

$$E_1 = n\,C_1\,\mathbf{N}, \text{ and } E_2 = n\,C_2\,\mathbf{N}; \text{ and}$$
$$E_1 = E - r_1 i_1, \text{ and } E_2 = e + r_2 i_2.$$

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[1] See *La Nature*, p. 43, 1882.

[2] Specification of Patent, 3940 of 1882; and *Electrician*, xix. 479, 1887.

[3] See *Electrician*, xix. 514, 1887; xx. 7, 1887; and Specification of Patent, 2130 of 1887.

[4] *Centralblatt für Elektrotechnik*, xi. 402, 1889.

Now write p for $C_1 \div C_2$ (the reciprocal of the *coefficient of transformation*), and we have—

$$p\,e = E - r_1\,i_1 - p\,r_2\,i_2.$$

But the electric work done on and by the armature is equal, assuming loss by eddy-currents and hysteresis to be negligible, or $E_1\,i_1 = E_2\,i_2$; whence $i_2 = p\,i_1$, so that the last equation becomes—

$$e = \frac{E}{p} - \left(r_2 + \frac{r_1}{p^2}\right) i_2.$$

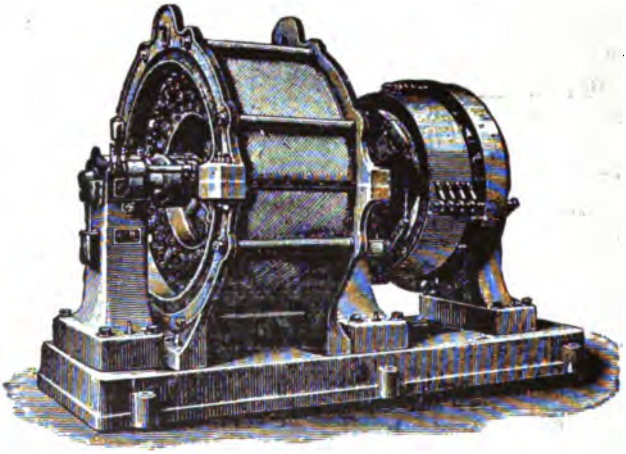
This shows that everything goes on in the secondary circuit as though the potential were reduced from that of the primary mains in proportion to the respective numbers of windings on the armature; and as though there were added to the internal resistance of the secondary circuit a resistance equal to that of the primary winding multiplied by the square of the coefficient of transformation. The ratio of transformation is independent of the speed and of the magnetism, though these two quantities depend inversely on one another. If the dynamo (or secondary) part is compound wound the speed may be very nearly constant at all loads; but there is little advantage in this, as the speed always adjusts itself to what is wanted. If the distant generator supplying the system is properly over-compounded it will keep the voltage at the lamps constant, though the transformer is interposed. The objections to the use as transformers of running machines are almost entirely met by the considerations that these machines run sparklessly (owing to the balancing of the self-inductions of the two windings), and with very little friction at the bearings, because the driving and driven parts are both contained in the one rotating part.

CONTINUOUS-ALTERNATING TRANSFORMERS.

To change an alternating current to a continuous one, or *vice versâ*, there is required a combination of an alternator and a continuous-current machine, to serve one as generator, the other as motor. This may consist of two separate machines coupled together, as shown in Fig. 479, which represents an alternator combined with an internal-pole continuous-current dynamo, both of Siemens' pattern, to transform from 2000 volts alternating to 150 volts continuous, for charging accumulators, &c.

But it is not necessary for this purpose to couple two separate machines. Consider the armature of any ordinary dynamo, say, a 2-pole ring machine. If, in addition to the ordinary commutator, there are provided two, three or four separate contact-rings, united severally to two, three or four points situated symmetrically around the ring,[1] such a machine may be used to give out or receive alternating currents of two, three, or four phases; one winding serving for both kinds of currents. Multipolar machines are preferable for this purpose as giving without undue speed of driving more rapid alternations than 2-pole machines. Such multiplex machines were shown at Frankfort in 1891 by Schuckert, Haselwander, and Dobrowolsky.

FIG. 479.



CONTINUOUS-ALTERNATING TRANSFORMER.

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[1] Such a machine—an "E" Gramme with two contact rings added by Dr. R. M. Walmsley—has been used for some years in the Technical College, Finsbury.

CHAPTER XXVI.

ELECTRIC TRANSMISSION OF ENERGY.

In all problems relating to the electric transmission of power, whether over short or long distances, it is vital to remember that there are two factors to be considered, the *current* and the *pressure* (or potential) at which it is transmitted. In the ordinary distribution of electric energy from central stations in cities, whether with direct or alternating currents, it is usual to observe the condition of *constant pressure*, the current being varied in proportion to the demand. But for series lighting, it is possible to observe the other condition of maintaining a *constant current*, the pressure being varied in proportion to the number of lamps in the circuit. It is well to bear this distinction in mind in the problem of transmission to a distance, although in fact power may be electrically supplied without conforming to either of these prescribed conditions of supply. We have seen, p. 560, how it came to be recognized that the secret of success in long distance transmission lay in the use of high voltages, as this permitted the use of small currents, and therefore of thin conducting wires. We may with advantage recapitulate the problem of economy of transmission.

It is required first to determine the relation between the potential at which the current is supplied to the motor, and the heat-waste in the circuit.

Let Σ R stand for the sum of all the resistances in the circuit; then, by Joule's law, the heat-waste is (in watts) $i^2 \Sigma \mathrm{R}$. And since $i = \frac{E - \mathrm{E}}{\Sigma \mathrm{R}}$, we may write:

$$\text{heat-waste} = \frac{(E - \mathrm{E})^2}{\Sigma \mathrm{R}}.$$

Now suppose that without changing the resistances of the circuit we can increase E, and also increase E, while keeping $E - \mathrm{E}$ the same as before, so that the current will be the same: it is clear that the heat loss will be precisely the same as before. But how about the work done? Let the two new values be respectively $\acute{E}$ and $\acute{\mathrm{E}}$. Then the electric energy expended is

$$\acute{\mathrm{W}} = \acute{E} i,$$

and the useful work done is

$$\acute{w} = \acute{\mathrm{E}} i.$$

That is to say, with no greater loss in heating, more energy is transmitted, and more work done. Also the efficiency is greater, for

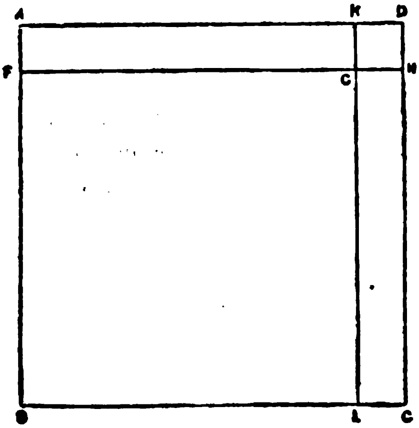
$$\frac{\acute{w}}{\acute{\mathrm{W}}} = \frac{\acute{\mathrm{E}}}{\acute{E}},$$

and this ratio is more nearly equal to unity than $\frac{\mathrm{E}}{E}$, because both E and E have received an increment arithmetically equal. As an example, suppose E to be 100 volts and E 90 volts, and the sum of the resistances to be 1 ohm. Then i will be 10 amperes. The power supplied will be 1000 watts; that utilized will be 900 watts; the heat-waste is 100 watts; and the electrical efficiency 90 per cent. Now suppose the voltages increased so that $\acute{E}$ is 1000 volts, and $\acute{\mathrm{E}}$ 990 volts. The current will still be 10 amperes. The power supplied will be 10,000 watts, of which 9900 will be utilized and 100 wasted in heat. We have 10 times as much power transmitted, with the same heat-waste as before, and the efficiency has risen to 99 per cent. Clearly, then, it is an economy to work at high voltage. The importance of this matter cannot be overrated. But how shall we obtain this higher electromotive-force? there are four ways open to us. [*i*] The simplest expedient is that of driving both generator and motor at higher speeds. The objections to this expedient are the purely mechanical considerations of liability to heating of bearings and centrifugal flying. [*ii*] A second way is to wind the armatures of both machines with many coils of wire having many turns. This expedient has, however, the effect of putting great resistance into the circuit. This circumstance may, nevertheless, be no great drawback, if there is already a great resistance in the circuit—as, for example, the resistance of many miles of wire through which the power is to be transmitted. In this case, doubling the electromotive-force will not double the resistance. Even in the case where the line resistance is insignificant, an economy is effected by raising the electromotive-force. For, as may be deduced from the equations, when $E - \mathrm{E}$ is kept constant, the effect of doubling the electromotive-force is to increase the efficiency, even when the resistance of the line is very small as compared with that of the machines, and to double it when the resistance of the line is very great as compared with that of the machines. It is, in fact, worth while to put up with the extra resistance, which we cannot avoid if we try to secure high electromotive-force by the use of coils of fine wire of many turns. [*iii*] A third way, not open to any of these objections, is to increase the magnetic field by employing a more powerful field-magnet. [*iv*] A fourth way is to put several machines in series with one another so as to add their separate electromotive-forces.

The advantage derived in the case of the electric transmission of energy from the employment of very high electromotive-forces in the two machines is also deducible from the diagram.

Let Fig. 372, given on p. 568, be taken as representing the case where E is 100 volts and E 80 volts. Now suppose the resistances of the circuit to remain the same while E is increased to 200 volts and E to 180 volts. (This can be accomplished by increasing the speed or the magnetism of both the generator and the motor to the requisite degrees.) $E - \mathrm{E}$ is still 20 volts, and the current will be the same as before. Fig. 480 represents this state of things. The square K G H D which represents the heat-waste is the same size as before; but the energy spent per second is twice as great, and the useful work done is more than twice as great as previously. High voltage, therefore, means not only a greater quantity of power transmitted, but a higher efficiency of transmission also. The efficiency of the system in the case of Fig. 372 was 80 per cent.; in the case of Fig. 480 it is 90 (the dynamos used being supposed "perfect"); and whilst double energy is expended, the useful return has risen 2¼ times.

FIG. 480.



In the attempt of M. Marcel Deprez to realize these conditions, in the transmission of power from Miesbach to Munich in 1882, through a double line of telegraph wire, over a distance of 34 miles, high electromotive-forces were actually employed. The machines were two ordinary Gramme dynamos, the magnets being series-wound, similar to one another, but their usual low-resistance coils had been replaced by coils of very many turns of fine wire. The resistance of each machine was 470 ohms, whilst that of the line was 950 ohms.[1] The velocity of the generator was 2100 revolutions per minute; that of the motor, 1400. The difference of potential at the terminals of the generator was 2400 volts; at that of the motor, 1600 volts. According to Professor von Beetz, the President of the Munich Exhibition, where the trial was made, the actual mechanical efficiency was found to be 32 per cent. In Deprez's later experiments, in 1886, between Creil and Paris,[1] the potentials were 6004 and 5456 volts respectively; and according to M. Levy the mechanical efficiency as measured by dynamometers was 44·81 per cent., the distance being about 36 miles. M. Deprez has given the rule that the efficiency $\frac{w}{W}$ is obtained, in the case where two identical machines are employed, by comparing the two velocities at the two stations. Or

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[1] These figures, and those which follow, are given on the authority of the President of the Munich Exhibition, Professor von Beetz.

$$\frac{w}{W}=\frac{n_2}{n_1},$$

Where n_1 is the speed of the generator, n_2 that of the motor. There is, however, the objection to this formula, that the electromotive-force are not proportional to the speeds, unless the magnetic fields of the two machines are also equally intense, and the current running through each machine the same. This is not the case if there is any leakage along the line. Further, even though the current running through the armatures and field-magnets in the generator which creates the current, and in the motor which utilizes the current, be absolutely identical the intensities of the magnetic fields of the two machines are not equal, even though the machines be absolutely identical in build: the reaction between the armature and field-magnet in the dynamo that is used as a motor is different from that in the dynamo which is being used as the generator.

In an experiment, M. Fontaine,[2] by using several Gramme machines coupled in series at each end of a line, the resistance of which was 100 ohms, succeeded in transmitting 50 horse-power with a mechanical efficiency of 52 per cent. This experiment realized the suggestion made in 1879 by Elihu Thomson for the economic use of several machines in series. Seven machines were used, of similar construction, resembling Fig. 325, and each weighing 1200 kilos., and of about 16 kilowatts capacity. Four were united in series at the generating end, and driven at 1298 revolutions per minute by a steam engine indicating 113 HP. Brake tests at the generating end showed the actual HP. to be 95·88. The other three machines were used as motors, their power being measured by a brake. They gave out 49·98 HP. at 1120 revolutions per minute. The current was 9·34 amperes. The result is that there was a nett efficiency of 52 per cent. The resistance of the machines was about 11½ ohms each. The voltage at the generating end of the line was 5996 volts: that at the receiving end was 5062 volts.

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[1] *Electrician*, xvii. 318, 1886.

[2] *L'Electricien*, x. 707, 1886.

EFFICIENCY OF TRANSMISSION.

It can readily be shown that with two series dynamos, the electrical efficiency of transmission, when there is no leakage, is the ratio of the electromotive-forces developed in the armatures of the two machines. To do this we will consider separately the efficiencies of the three parts of the system. Writing E_1 for the electromotive-force developed in the generator, E_2 for that of the motor, r_1 and r_2 for their respective internal resistances, we shall then have

$$\text{Efficiency of generator} \;..\; \eta_1 = \frac{E_1 i - r_1 i^2}{E_1 i};$$

$$\text{Efficiency of line} \;..\;..\; \eta_2 = \frac{E_2 i + r_2 i^2}{E_1 i - r_1 i^2};$$

$$\text{Efficiency of motor} \;..\;..\; \eta_3 = \frac{E_2\, i}{E_2 i + r_2 i^2}.$$

Hence the resulting efficiency of the whole system will be

$$\eta = \eta_1 \times \eta_2 \times \eta_3 = \frac{E_2}{E_1}.$$

If the machines are shunt-wound or compound-wound, or if there is leakage on the line, the currents through the armatures will no longer be alike in the two machines. Writing the respective armature currents as i_1 and i_2 we shall have in this case, as the electrical efficiency of transmission,

$$\eta = \frac{E_2\, i_2}{E_1\, i_1}.$$

As an example we may refer to experiments[1] made in 1887 with Brown's direct-current dynamos (Plate IX.), between Kriegstetten and Solothurn, through a conductor of 9·23 ohms resistance. In one experiment, the observed values were—E_1 1231·6, E_2 988·6, i_1 14·204, i_2 14·177. The actual horse-power measured at the two ends showed a nett mechanical efficiency of 74·7 per cent. In this case the *nett* efficiency of the generators was 88·8 per cent., that of the motors was 88·1 per cent., whilst the efficiency of the line was 95·4 per cent.

Another example[2] of transmission with direct currents is afforded by the plant at Steyermuhle (Tyrol), where two of Brown's 2-pole dynamos with Gramme rings are used to send about 8 HP. to a distance of 600 metres through a double line of copper wire. The following are particulars of the machines. *Generator*, 67 amp. at 1000 volts at terminals, at 575 revs. per min. Turns of wire on armature 504, in 126 sections of 4 turns each. Diam. of core rings, 70 cm. Diam. of magnet cores 40 cm. These are series-wound with 371 turns each. *Motor* only differs in having 456 turns on armature in 114 sections of 4 turns each, and with diam. of magnet-cores 38·1 cm. Brake measurements showed that the generator absorbed 98 HP., whilst the motor gave out 79 HP.; a commercial efficiency of 86 per cent.

A simple problem in the electric transmission of power is the following:—Suppose that one were desirous of working a motor, so as to do work at the rate of a specified number of horse-power, and that the wire available to bring the current cannot safely stand more than a certain current, without being in danger of becoming heated unduly. It might be desirable to know what electromotive-force such a motor ought to be capable of giving back, and what electromotive-force must be applied at the transmitting end of the wire. Let P stand for the number of horse-power to be transmitted, and i for the maximum strength of current that the wire will stand (expressed in amperes). Then by the known rule for the work of a current, since

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[1] See H. F. Weber, in *Schweiz. Bauzeitung*, xi. Nos. 1 and 2, 1888; and *Journ. Soc. Telegr. Engineers*, xvii. 337, 1888.

[2] *Elektrotechnische Zeitschrift*, xi. 11, 1890.

$$\frac{\mathrm{E}\, i}{746} = \mathrm{P},$$

$$\mathrm{E} = \frac{746\,\mathrm{P}}{i}$$

gives the condition as to what electromotive-force (in volts) the machine must be capable of giving, when run at the speed it is eventually to run at as a motor. Moreover, the primary electromotive-force, E, must be such that

$$\frac{E - \mathrm{E}}{\Sigma\,\mathrm{R}} = i,$$

where Σ R is the sum of all the resistances in the circuit. Whence

$$E = \mathrm{E} + i\,\Sigma\,\mathrm{R}.$$

Which gives the required primary electromotive-force.

GRAPHIC METHODS APPLIED TO MOTOR PROBLEMS.

Of the following problems, the first two relate to series motors, and are due to Dr. E. Hopkinson and to Mr. Alexander Siemens.[1]

Given a system of distributing mains supplying electricity at a constant potential, E, it is required to construct a motor which when working with a given load shall make n revolutions per minute.

Taking, in Fig. 481, as usual, the currents as abscissæ, and the electromotive-forces as ordinates, draw O M to represent the potential E of the main in volts. Now, makers of dynamos know from experience what percentage of the electrical energy supplied to a machine of the type they make is absorbed in maintaining the magnetic field. Take a point N in O M such that N M $\div$ O M represents this percentage. Also it is known what percentage of the energy thus taken up by the armature, and converted into mechanical work, is wasted in friction at the bearings and brushes. Take the point R such that N R $\div$ O N represents the percentage so wasted. From O x cut off O H such that the area O H R′ R represents the actual mechanical output of the motor in watts. For example, if the motor is to realize 1 horse-power, then the area O H R′ R must equal 746 watts. Then O H represents the current (in amperes), and H P is the counter electromotive-force which the motor must exercise. The motor, then, must be such that, running at *n* revolutions per minute,

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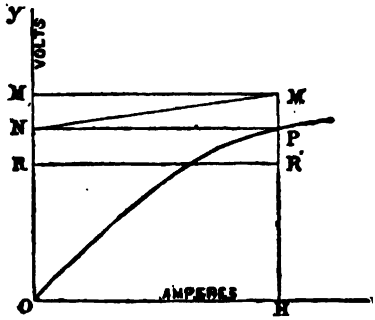
[1] *Journal of the Society of Arts*, April 1883.

FIG. 481.



its characteristic will pass through P. The economic coefficient will obviously be equal to H P ÷ H M, and the nett efficiency to H R′ ÷ H M′. The energy spent in magnetization is measured by the area N P M,′ the tangent of the angle P N M′ represents the resistance of the armature, and of the magnets in the case of a series motor.

It is possible to work out similar problems for a shunt-wound motor, and also for the case of a distribution with a constant current.

Given a motor needing a certain current and a certain electromotive-force to enable it to do its work, it is required to construct a suitable generator, the distance between the machines being represented by an electrical resistance of R *ohms.*

Let O P P′ (Fig. 482) be the characteristic of the motor running at its required speed ; P H being the volts, and O H the current needed for it. Draw P N horizonally ; and draw N M′ from N at an angle such that its tangent represents the sum of the resistances of the motor and line. Then M′ H represents the difference of potential between the terminals of the generator. Then produce H M′ to Q so that H M′ ÷ H Q shall represent the economic coefficient of the machine of the type that is to be used as generator. Then the proper generator will be that which when running at the proper speed will have a characteristic running through O and Q ; and the tangent of the angle M′ M Q represents the resistance of the armature and field-magnet of the generator.

Another graphic method of comparing the power and efficiency of a motor has been proposed by Mr. Gisbert Kapp. The speeds being taken as abscissæ, the electric horse-power absorbed is plotted out vertically, the number of watts divided by 746 being taken for the ordinates. Fig. 483 shows the result in the curve A A, the shape of which will vary with the type, a series-wound motor in this case. A second curve B B is then plotted, the ordinates in this case being the mechanical horse-power observed at different speeds. In both cases the variation of speed is obtained by loading a brake dynamometer with various loads. With a great load the speed is small, the applied electromotive-force very great. With no load, a certain maximum speed O M is obtained at which (owing to the counter electromotive-force developed) very little current passes. Between these two extremes there will be a point *b*, corresponding to a certain

FIG. 482.

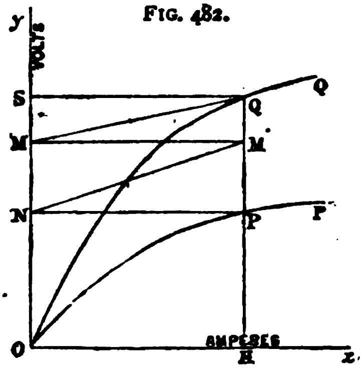
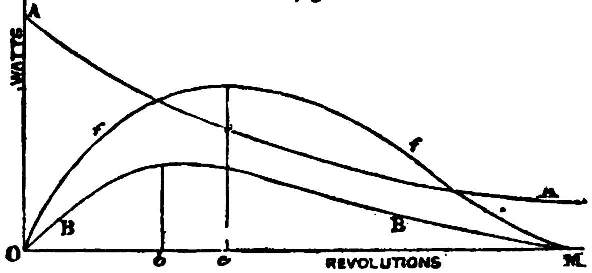


FIG. 483



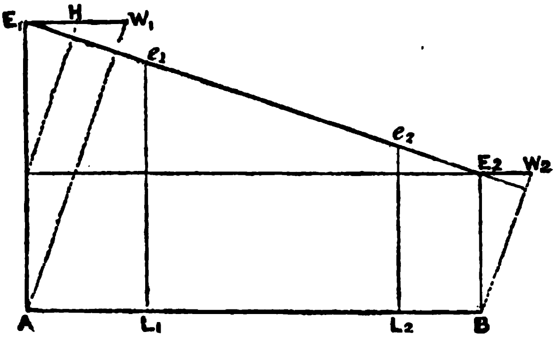
speed O *b*, for which the activity is a maximum. Next divide the values of the mechanical work B, by those of the electrical energy spent E at the corresponding speed. These quotients will of course be the commercial efficiency at different speeds. These values are plotted out to an arbitrary scale in the curve *f f*, which shows that the maximum efficiency is attained at the speed corresponding to the point *c*.

GRAPHIC REPRESENTATION OF TRANSMISSION.

A convenient mode of representing graphically the relative amounts of energy expended at the transmitting end and utilized at the receiving end is the following, which is due to von Hefner Alteneck :—

Let (Fig. 484) the perpendicular lines A E_1 and B E_2 represent respectively the electromotive-forces at the transmitting and receiving machines ; and let the horizontal lengths A L_1, L_1 L_2, and L_2 B represent respectively the resistances of the machine at A, the line (including return wire), and of the machine at B. Join E_1 E_2 : the tangent of slope of this line will represent the current flowing. From A and from B drop perpendiculars upon this sloping line, and produce them to the points W_1 and W_2, level with E_1 and E_2. The lengths of the lines E_1 W_1 and E_2 W_2 will represent relatively the energy transmitted and received. For, by the construction each is proportional to the respective electromotive-force and to the slope of E_1 E_2. The energy lost in heat may, on the same scale, be represented by the length of the line E_1 H.

FIG. 484.



For a further geometrical discussion of the problem of electric transmission of power, see a paper by Reignier, in *La Lumière Electrique*, xxiii. 352, 1887.

ECONOMY OF TRANSMISSION.

As already shown, the economy of transmission depends on the voltage at which the power is transmitted, and on the resistance of the line. The question then arises at what amount ought the latter to be fixed to make the economy a maximum. If one saves heat-waste by putting up a thick copper wire for the line, the interest on the prime cost of the line may more than balance the saving in power. An answer was given in 1881, by Sir William Thomson, to one form of the problem, in which it is assumed (1) that the voltage is fixed, (2) that the power to be transmitted is a fixed amount. If these are the conditions, then the total annual cost of the power wasted in the resistance of the line and of the interest on the copper (including insulation and erection) will be a minimum when these two annual items of cost are equal to one another. Much confusion has arisen from the ignorant application of Thomson's law to other cases than those for which it is true. In 1886, Professors Ayrton and Perry[1] considered some other cases, and have arrived at several important conclusions. If a given amount of power has to be furnished by a motor at one end of a line, using a given voltage at the generator at the other end, maximum economy is obtained, not by keeping the current-density constant, but by making it less, as the length of line to be used is greater. The smaller the voltage that may be employed at the generator, the smaller must the current-density in the line be to obtain the maximum efficiency. More recently, Mr. Kapp,[2] in his Cantor Lectures, has given a more general solution, taking into account the voltage and the cost of the machines as well as that of the line. It is assumed that the annual value of power at the generating station is known, as well as the cost of plant per horse-power. Of the data required to be known, such as primary horse-power, total efficiency, voltage at motor, annual cost of power delivered, and working current, the last mentioned is the most important to be calculated, for from it the other matters can then be found. The following is then Kapp's argument :—

MOST ECONOMICAL CURRENT FOR ELECTRIC POWER TRANSMISSION.

D	Distance in miles.
a	Section of conductor in square inches.
E	Terminal volts at generator.

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[1] *Journal Soc. Telegr. Engineers*, xv. 120, 1886.

[2] *Journal Soc. Arts*, xxxix., July 10, 1891.

e	.. Terminal volts at motor.
HP_g	.. Actual horse-power required to drive generator.
HP_m	.. Actual horse-power obtained from motor.
i	.. Current in amperes.
	Efficiency of generator 90 per cent.; efficiency of motor 90 per cent.
g	.. Cost in £ per electrical horse-power output of generator.
m	.. Cost in £ per actual horse-power output of motor including regulating gear.
$G = \cdot 9 g\, HP_g$	.. Cost in £ of generator.
$M = m\, HP_m$	.. Cost in £ of motor and regulating gear.
$t = 18{\cdot}2\, D a$	.. Weight in tons of copper in line.
K	.. Cost in £ per ton of copper, including labor in erection.
s	.. Cost in £ of supports of line per mile run.
p	.. Cost in £ of one annual actual horse-power absorbed by generator.
q	.. Percentage for interest and depreciation on the whole plant.

$$\text{Capital outlay} = g\,\frac{Ec}{746} + m\,HP_m + Ds + \frac{1{\cdot}6\,K D^2 c^2}{Ec - 830\,HP_m} = A.$$

$$\text{Annual cost per brake horse-power delivered} = q\,\frac{A}{HP_m} + p\,\frac{HP_g}{HP_m}.$$

$$\text{Put } B = \frac{Ep}{670} + q\,\frac{Eg}{746}.$$

$\gamma = \frac{830}{E}\,HP_m$, the current which would be required if the line had no resistance,

and $\beta = \gamma^2 \frac{EB}{1{\cdot}6\,q\,KD^2 + EB}$; then the most economical current at the given voltage E is

$$i = \gamma\left\{1 + \sqrt{1 - \frac{\beta}{\gamma^2}}\right\}$$

$$i = \gamma\left\{1 + \sqrt{\frac{1{\cdot}6\,q\,KD^2}{1{\cdot}6\,q\,KD^2 + BE}}\right\}.$$

For very long distances the term under the square root approaches unity and the most economical current the value 2γ; from which it follows that under no circumstances will it be economical to lose more than half the total power in the line.

A useful set of tables, showing the cost of laying one additional ton of copper, meaning thereby that part of the capital outlay which is proportional to current, was given by Prof. G. Forbes in his Cantor Lectures[1] of 1885 on the Distribution of Electricity.

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[1] *Journal Soc. Arts*, 1885.

The secret of economy in all long-distance transmission lies, as we have seen, in the use of high voltage. But it is found in practice that continuous-current machines cannot advantageously be used at such high voltages as 3000 and 4000 volts, inasmuch as the commutators will not stand the strain on their insulation. Even putting several machines in series, though it lessens the voltage on each dynamo, does not prevent the risk of break-down of insulation. Hence the superiority of alternate-current apparatus, which requires no commutator. Moreover, where voltages exceeding 10,000 volts are desired, it is found preferable to use low-voltage alternators and motors, and to insert step-up transformers at the generating end, and step-down transformers at the receiving end (as proposed in 1881 by Deprez and Carpentier), since it is much easier to insulate thoroughly the stationary windings of a transformer than the parts of any running machinery. The question whether of alternating systems the ordinary two-phase, or one of the more novel three- or four-phase systems, is to be preferred in long-distance transmission is still an undecided matter.

As an example of transmission to a moderate distance by continuous currents, we may cite the plant at Schaffhausen, erected by the Oerlikon Works of Zurich, where 500 actual horse-power are delivered to the spinning mills electrically, with a nett efficiency of 78 per cent., from turbines in the river 750 yards away, two generators (six-pole over-compounded dynamos designed by C. E. L. Brown) being used, to give each 330 amperes at 624 volts. The motors, which are of the same type, are constructed with field-magnets, which are relatively more powerful than those of the generators, and run without varying more than 3 per cent. in speed between no load and full load. The commutators are guaranteed to last for 20,000 hours.

As an example of long-distance transmission at an extra-high voltage may be cited the experimental line erected in the summer of 1891, from Lauffen to Frankfort, a distance of 175 kilometres. At Lauffen a special low-pressure turbine was fixed in the river Necker to drive the three-phase alternator, by Brown, described on p. 688, capable of giving (at full power) three alternating currents of about 1400 amperes each at 50 volts. These currents were converted by special transformers into three smaller currents at either 12,500 or 25,000 volts. Three copper wires, each 4 millimetres in diameter, were carried to Frankfort on tall poles; about 10,000 porcelain insulators being employed, with oil-cups for high insulation. At Frankfort the currents were received into step-down transformers and reconverted to the low-pressure of about 60 volts, to supply either lamps or three-phase motors. Tests[1] were made by a jury, having Prof. H. F. Weber as its head.

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[1] Whilst these sheets are going through the press, unofficial information comes to hand about the yet unpublished tests. It appears that when the high-pressure of 30,000 volts was used the watts supplied at Lauffen were 80,500, and the watts actually received and used at Frankfort were 58,000; showing the gratifying result of an efficiency of 72 1-6 per cent.

CHAPTER XXVII.

REGULATORS FOR DYNAMOS.

Means of governing the performance of dynamos are needed, not only for keeping the pressure at some constant number of volts or for keeping current at some constant number of amperes, but also for such purposes as to enable the voltage of any one dynamo to be raised in order that it may feed into some distant point of a distributing network.

The output of a dynamo depends on three intrinsic matters, namely, (*i*) speed *n*, (*ii*) number of armature conductors C, and (*iii*) magnetic flux N; and on two extrinsic matters, namely (*iv*) resistance of the circuit and (*v*) counter electromotive-forces in the circuit. It is therefore clear that any one of these five matters might afford a method of controlling the performance of the machine.

To introduce resistances into the main circuit is always wasteful, and may be dismissed as an uneconomical method of regulation suitable only for experimental purposes. To introduce counter electromotive-forces into the external circuit is usually impracticable. It remains therefore to consider the three intrinsic methods.

Speed governing is clearly limited to those cases where there is a separate engine for each dynamo; and in such cases a special governor will be required instead of the usual centrifugal engine governor.

To alter the number of conductors in a rotating armature whilst it is running is absurd. Their *effective* number can, however, be altered by the device of shifting forward the brushes so that they collect the current not at the point of highest potential, but at some other point. This method virtually uses some of the armature windings, namely, those between the neutral point and the point to which the collecting brush is advanced, to produce internal counter electromotive-forces.

To alter the magnetic flux is the almost universal mode of control; and it may be accomplished in two entirely distinct kinds of way. Since the flux depends on the excitation (or ampere-turns) and on the reluctance of the magnetic circuit, it can be varied by varying either the former or the latter. The excitation may be altered in various ways, (*a*) by hand with the aid of rheostats and commutators in the exciting circuit, or (*b*) automatically by special governors in substitution for the hand, or (*c*) by devices of compound winding. The magnetic circuit may be varied in several ways, as (*d*) by moving the pole pieces nearer to or further from the armature, (*e*) by opening or closing some other gap in the magnetic circuit, (*f*) by drawing the armature end-ways from between the pole-pieces, (*g*) by shunting some of the magnetic lines away from the armature by applying a magnetic shunt across the limbs. All these magnetic devices have been tried,[1] but not with much success except in small machines.

Hand-regulators.—These consist of sets of sliding contacts to enable the operator to perform one of the following operations:—(1) insert or remove resistance from the exciting circuit of a shunt dynamo (see Edison's Regulator, Fig. 180, p. 279); (2) insert or remove resistances, shunting the magnetizing coils of a series dynamo; (3) cut out more or fewer exciting coils, these being grouped in sections.

CONSTANT PRESSURE AND CONSTANT CURRENT REGULATORS.

In all automatic regulators there is a part which has to act as the brain of the instrument, watching as it were against any variation, and setting into action the mechanism which is to counteract the variation. This watching device is usually some sort of an electromagnet, often a coil with a movable plunger. When the volts are to be kept constant the coil of the controlling device must be wound as a voltmeter coil, that is of fine wire, of high resistance, and connected as a shunt. When the amperes are to be kept constant the controlling coil must be wound like an amperemeter with thick wire, of low resistance, and inserted in the main circuit. Alternators are usually regulated by operating on the circuit of their exciters, the current in the governor coil being derived from the mains by a small transformer.

Goolden's Automatic Regulator.—Automatic regulators are of two species: in one the work of moving the regulator is accomplished mechanically, the control only being electrical; in the

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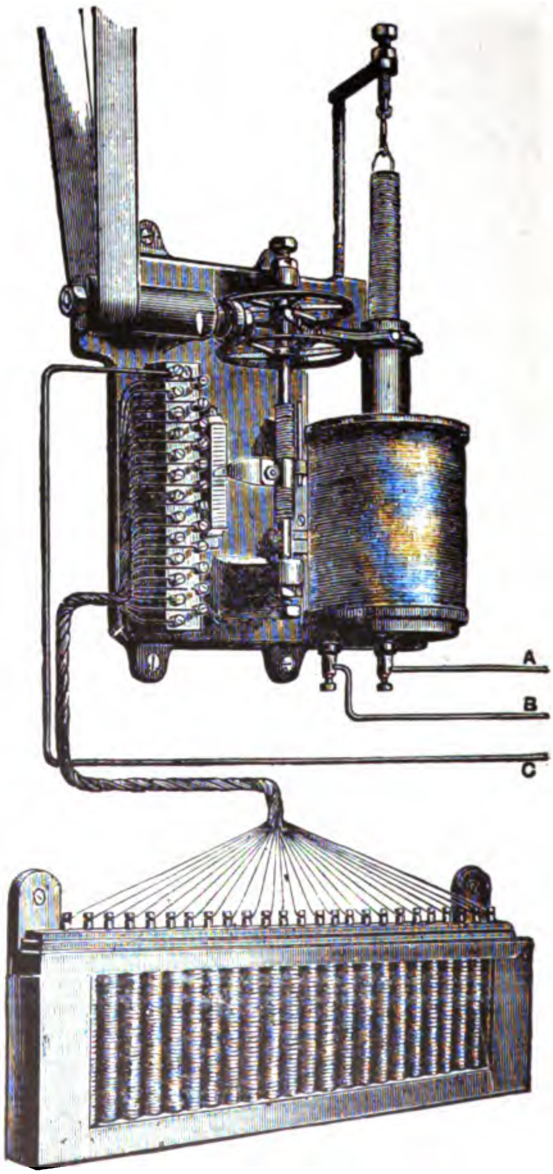
[1] For an example of (*d*) see Firth's method (see *Industries*, ix. 161), in which the polar masses are drawn backwards by screws; and of (*g*) a magnetic shunt applied by Desroziers, *La Lumiere Electrique*, xxiv. 394. Other magnetic methods have been used by Goolden and Trotter, Langley, P. Müller, Lontin, and Diehl.

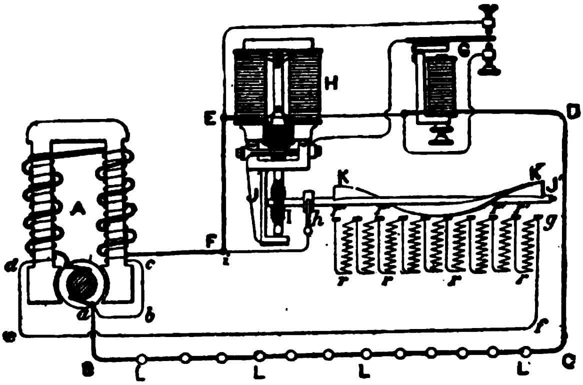
FIG. 485.



GOOLDEN'S AUTOMATIC REGULATOR.

other both the control and the moving power are obtained electrically. Goolden's regulator, Fig. 485, belongs to the former of these classes. In this instrument there is a row of sliding contacts which are respectively connected to the wires of a resistance-frame or rheostat[1] shown in the lower part of the cut. The sliding piece is worked by a vertical screw, and this is caused to rotate right or left-handedly as may be required under the operation of a double crown-wheel on a sleeve on the vertical spindle, placed between two screws that are kept in rotation by a small pulley driven slowly from the engine. The controlling part—the brain of the apparatus—is the hollow coil of wire on the right, with its suspended iron plunger. When the current in this coil is of proper normal strength the plunger is drawn in just so far that the crown-wheel is not in gear either with the upper or the lower driving screw. If the current in the coil grows weak the plunger rises, causing the crown-wheel to engage in the upper screw, which immediately begins to turn it, so moving the sliding-contact in such a way as to increase the excitation of the dynamo, and bring back the current in the coil to its normal strength. The wires A and B from the governing coil go to the circuit that is to be kept to standard condition, whilst the exciting circuit of the dynamo is connected to C and to the sliding piece.

Fig. 486.



Maquaire's Regulator.

Maquaire's Regulator is an example of the second kind, both the controlling and the moving mechanisms being electrical. The governor G consists of an electromagnet, the armature of which is attached to a spring, and when the current through it—in the main circuit of a set of lamps, L L in Fig. 486—is normal, is so balanced that the tongue attached to it lies free between two contact-screws. The dynamo A has two exciting coils. One in the main or lamp circuit: the other is a shunt circuit *a b c d e f g h i*, in which are included the coils *r r* of a rheostat. The contacts of this rheostat are operated by turning a shaft J J, having a tortuous contact-piece K K upon it. The mechanism which turns the shaft J J is a small electric motor, the field-magnets of which H are in the main circuit. By a device explained on p. 593, the armature of this motor can be made to turn in either direction by being made a shunt to either half of the field-magnet of the motor; one brush being connected to the magnetizing coils mid-way between the two limbs, the other being connected to the tongue of the governor G. Hence if the main current becomes too weak the tongue rises, and making contact, causes the motor armature to turn so as to alter the resistance and increase the excitation of the dynamo.

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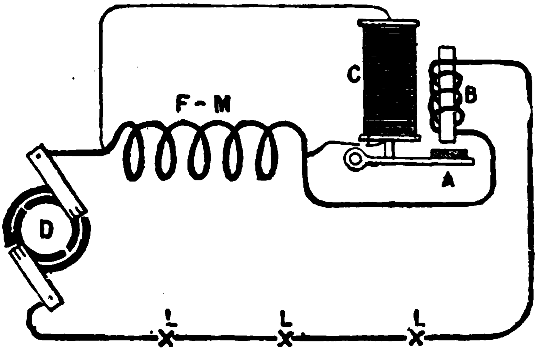
[1] On the construction of such rheostats, choice of wires, and the like, see Herrick, *Electrical World*, xv. 240, 1890; also Ayrton and Mather, *Phys. Society*, 1891.

Brush's Automatic Regulator.—This is a simpler example of a purely electric regulator. A series dynamo is made to yield a constant current by introducing across the field-magnets a shunt of variable resistance, the resistance of the shunt being adjusted automatically by a governing electromagnet whose coils form

FIG. 487.



BRUSH'S AUTOMATIC REGULATOR.

part of the main circuit. The system is shown in the accompanying diagram (Fig. 487). The dynamo at D pours its current into the circuit, leaving the commutator (as drawn) by the upper brush, whence it flows through the field-magnets F M, and round the circuit of lamps L L, back to the negative terminal. Suppose now some of the lamps to be extinguished by switches which short-circuit them; the resistance of the circuit being thus diminished there will be at once a tendency for the current to increase above its normal value unless the electromotive-force of the dynamo is at once correspondingly reduced. This is done by the solenoid B in the circuit. When traversed by the normal current it attracts its armature A with a certain force just sufficient to keep it in its neutral position. If the current increases, the armature is drawn upward and causes a lever to compress a column of hard carbon plates C, which is connected as a shunt to the field-magnets. These plates when pressed together conduct well, but when the pressure is diminished their imperfect contact partially interrupts the shunt-circuit and increases its resistance. When A rises and compresses C, the current is diverted to a greater or lesser extent from the field-magnets which are thus under control. This regulator will keep the current constant even though the speed of driving may be irregular.

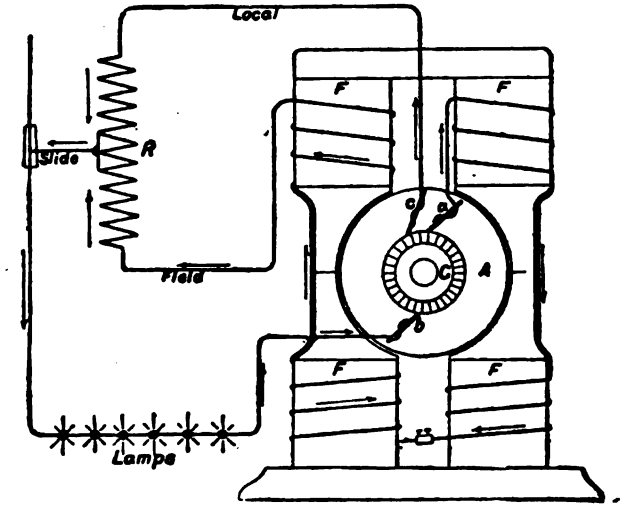
Thomson-Houston Regulator.—This was described on p. 471, and operates by shifting the brushes so as to bring counter electromotive-forces into play, and is purely electrical.

Statter's Regulator.—This was described on p. 478, and shifts the brushes by a motion derived mechanically from the rotation of the dynamo, but electrically controlled.

Waterhouse's Third Brush Regulator.—In this case the exciting circuit on the dynamo receives and carries a variable part of a current supplying arc lamps in series as in Fig. 488, the other part being carried by a local circuit which, starting from a third brush, joins the lamp circuit at a certain point along a resistance in the circuit. In Fig. 488 the positive brush is marked *a*, and leads through the exciting coils to the resistance R, and there is joined by the local branch from the third brush *c*. The action depends on the armature reaction altering the point of highest potential at the commutator. If, on cutting out one or more lamps, the current in the armature were to increase, the position of maximum potential would be shifted from *a* towards *c*, causing more current to flow by the local branch, and less by the exciting branch, so bringing down the excitation. A special study of this method of regulation has been made by

Caldwell,[1] who has shown that it can also be applied to constant pressure regulation.

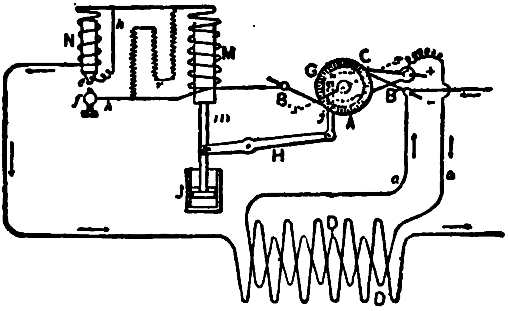
FIG. 488.



WATERHOUSE'S THIRD-BRUSH REGULATOR.

Wood's Regulator.—In this method also a pilot brush is employed, but there are two exciting circuits wound differentially, and there is an electromechanical device for shifting the brushes,

FIG. 489.



WOOD'S REGULATOR.

attached to the dynamo, Fig. 320, p. 476. In the regulator, Fig. 489, the governor coil N actuates a core, the motion of which opens or closes a by-pass circuit of an electromagnet M, which moves the rocker to which the two brushes are attached. When all the lamps are in circuit and the dynamo fully excited, the pilot-brush C is close to B, so that almost no current flows around the demagnetizing circuit *a a*. If now some lamps are cut out,

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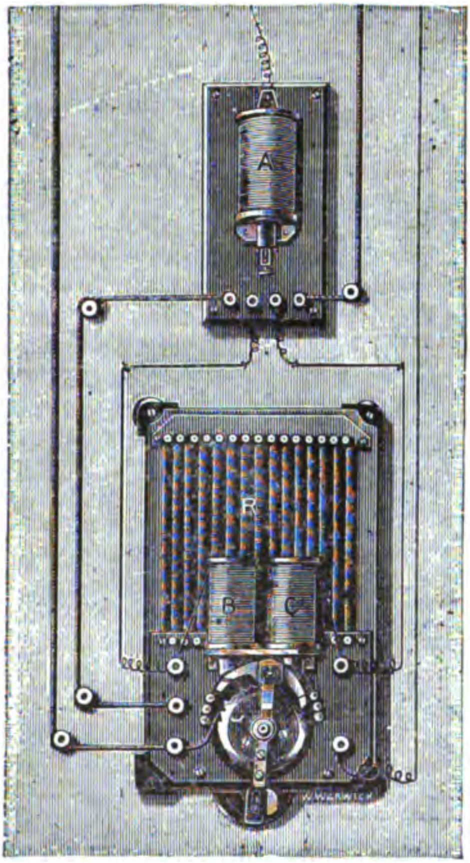
[1] *The Electrician*, xxii. 217, 1888; and remarks by Prof. Nicholls, *ib.*, 441, 1889.

FIG. 490.



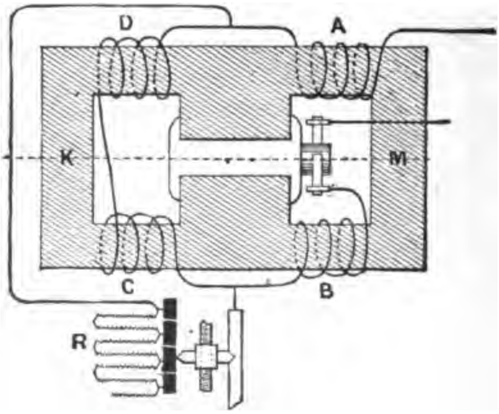
HENRION'S REGULATOR.

momentarily increasing the current above normal value, the governor core rises and breaks contact at *e f*, causing M to shift the pilot-brush C forward, so that the demagnetizing current is strengthened, so reducing the excitation. Sparking at *ef* is minimized by the resistance *r*.

Henrion's Regulator.—Another electromechanical regulator is shown in Fig. 490. The plunger of the governor A, on moving up or down from normal position, works the mechanism by short circuiting one or other of two electromagnets B and C, both of which are also in the main circuit. Below them is an oscillating lever pivoted on a pin carrying two ratchet wheels; and lever carries a double-ended iron pawl. If either magnet is cut out by the governor, the pawl drops over and at once begins to take up teeth on one of the ratchet wheels, thereby moving a contact arm over studs that communicate with the wires of a rheostat.

Ravenshaw and Trotter's Regulator.—This is an interesting example of the use of a magnetic shunt to produce a constant current. In the arrangement in question the number of magnetic lines through the armature core is reduced to any desired degree, without producing instability, while the field-magnet is saturated to its usual degree, by diverting the magnetic lines out of their usual path, into a path of lower magnetic reluctance. The plan of employing a movable keeper of iron was superseded by Trotter's suggestion to fix the keeper and to vary its effect by surrounding it with a counter-magnetizing coil. The double-circuit type of field-magnet is suited for this purpose, one half of the machine being kept saturated as a field-magnet of constant power, whilst the other half acts a keeper. In Fig. 491 the act-

FIG. 491.



RAVENSHAW AND TROTTER'S MAGNETIC SHUNT.

ing field-magnet is the right-hand half M, with the magnetizing coils A and B; the keeper is the left-hand half K, with the coils C and D. These four coils are connected up in the usual way to give consequent poles at the pole-pieces, but there is a regulating set of resistance R arranged as a shunt to the coils C and D. When the resistance R is small, the coils C and D scarcely receive any current, and consequently nearly the whole of the magnetic lines generated in the magnet pass round the keeper instead of through the armature. By introducing resistance at R the coils C and D begin to excite a counter magnetism and drive back some of the lines out of the keeper and into the armature. The resistances at R are arranged in a graduated set provided with contact pieces, with which contact is made by a slider worked by a governor, such as Fig. 485. It was found necessary[1] to cut a gap in the magnetic circuit of the keeper to prevent sluggishness in the descending magnetizations.

Sperry's Regulator.—This has a mechanical movement for shifting the brushes, operated from the shaft of the dynamo, but electrically controlled. It is shown in Fig. 318, p. 475.

M. Reignier[2] has drawn attention to a solution of the problem of exact governing to procure a constant current by automatically varying the number of coils through which the current is permitted to pass.

ELECTRIC GOVERNORS FOR STEAM-ENGINES.

No centrifugal governor attached to the steam-engine can keep the speed of the dynamo truly constant; for it does not act until the speed has become either a little greater or a little less than the normal value. Few mechanical governors will keep the speed within 5 per cent. of its proper value, under sudden changes of load. Hence the suggestion which underlies all electrical governors, that the admission of steam from the boiler to the engine should be controlled by the electric current itself, the speed of driving being varied according to the demands of the circuit. It is emphatically needed wherever the loads are liable to sudden variations, as in the case of generators for electric railways. Numerous suggestions of a more or less practical nature have been made by Lane-Fox, Andrews, Richardson, and others.

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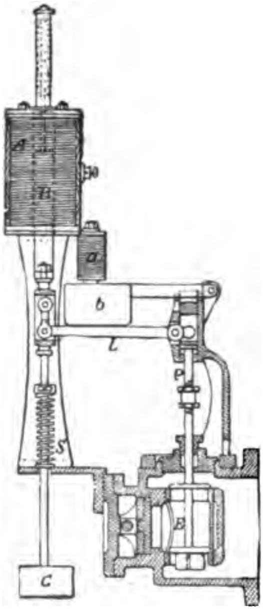
[1] See paper by A. P. Trotter, in *Electrician*, xix. 374, 1887. A drawing of the governor itself is given in the *Electrical Review*, xix. 289, Sept. 17, 1886.

[2] *La Lumière Electrique*, xxvi. 420, 1887.

Richardson's Governor.[1]—This governor is used to maintain either a constant current or a constant potential. In the former case its coils are included in the main circuit and are of thick wire : in the latter they are arranged as a shunt to the mains and are of fine wire. The arrangements are shown in Fig. 492.

Fig. 492.



Richardson's Electric Governor.

The valve which admits steam to the engine is a double-beat equilibrium valve E ; its stalk passes upwards and is acted upon by a plunger P, which is pressed down by the shorter end of the lever L, which is in turn connected with a long vertical spindle having a weight C at its lower end, and at its upper end carrying the iron core B, surrounded by the solenoid A. A spring S counterpoises the slight upward pressure of the steam on the valve. When the current passes through the solenoid A, it lifts the core B to a certain height and admits to the engine a sufficient quantity of steam to drive the engine at the speed requisite to maintain the current. Should the resistance of the circuit be increased by the introduction of additional lamps, the core B will fall a little, thereby turning on more steam, until the speed has risen to that now necessary. For additional safety a separate electromagnet *a* is added, which, when in action, holds up the heavy iron block *b*. Should the circuit from any cause be broken, the block *b* instantly descends and cuts off the steam. In some experiments made at Lincoln in 1883, in the author's presence, on a Brush 16-light machine fitted with a Richardson's governor, the following results were attained :—Seventeen arc lamps being alight, six were suddenly switched off : in four seconds the speed of the engine came down from 138 to 107, and the current which was 10·2 amperes had returned to exactly the same value. Seventeen lamps being again alight, the whole were short-circuited, leaving the current running only through the governor and the field-magnets of the dynamo. The engine pulled up in less than one stroke, and in fourteen seconds the speed had come down to 24.

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[1] See Specification of Patent, No. 288 of 1881.

the engine just crawling round at a speed sufficient to keep the magnets charged. In another experiment the circuit of the whole seventeen lamps was suddenly broken, the engine running at 140. In fifty-five seconds it had stopped, the steam having been cut off in less than a quarter of a second. No centrifugal governor could have so instantaneously shut off steam : it would not have acted until the engine began to race. With the electric governor the steam was cut off before racing could even begin. At all speeds from 25 up to 146 revolutions per minute, and with any number of lamps from none to seventeen alight, the current was practically kept at a constant value in a most efficient manner. Another of these governors connected with an incandescent-light system working at 92 volts was found to keep the potential correctly to within 1 per cent., even though the number of lamps was varied from 91 to 31, and the boiler-pressure from 32 to 55 lbs. per square inch. It also maintained an absolutely constant potential when but one lamp was alight, though the boiler-pressure was purposely varied from 31 to 55 lbs. per square inch.

Willans' Governor.[1]—This instrument has been applied with great success at Victoria Station and elsewhere. In common with Richardson's governor, it employs the attraction exerted by a solenoid on an iron core to actuate an equilibrium valve; but the action is indirect, the solenoid core operating on the small value which controls a hydraulic piston, the latter in turn controlling the large steam valve. The arrangement is shown in Fig. 493, where T is the large piston throttle-valve. The throttle-valve spindle passes downwards and is connected direct to the piston of the hydraulic relay. The solenoid A attracts its core B suspended on a spring. The position of B determines that of the lever X, which is connected at one point to the spindle of the throttle-value and at another to that of the small controlling valve. If the potential at the mains falls, less current flows round A, in consequence B rises, and its projecting ear-piece raises the lever X, admitting more water above the controlling piston, which consequently sinks, drawing down the throttle-valve with great power and admitting more steam to the driving engine. A comparatively small solenoid, actuated by but 0·3 ampere of current and absorbing only about 32 watts of power, may thus bring a force of many pounds to bear upon the steam valve, and will control with ease a 60 horse-power engine.

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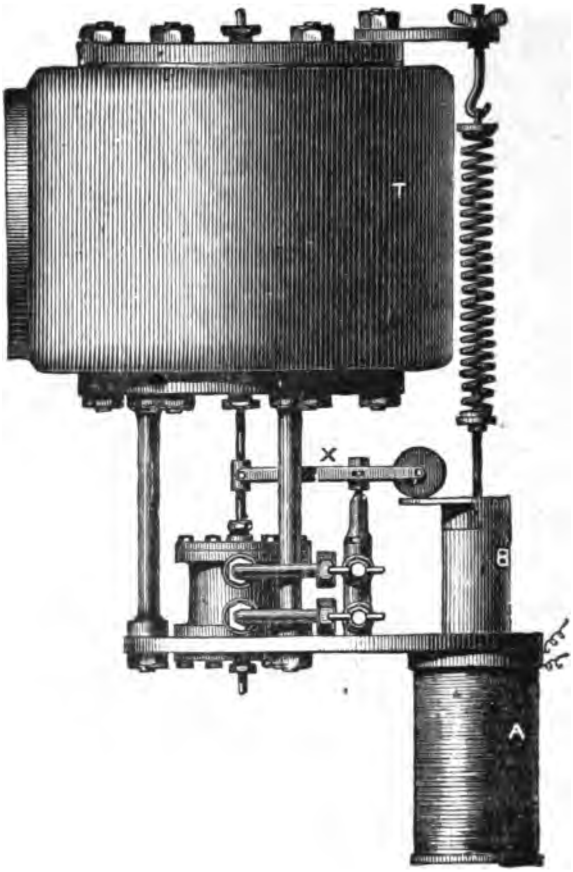
[1] See Specifications of Patent Nos. 1184, 5291, and 5945 of 1883; also paper by P. W. Willans in *Proc. Inst. Civil Engineers*, lxxxi. pt. iii. 1884–5.

FIG. 493.



WILLANS' GOVERNOR.

Jamieson's Governor.—This consists of a copper disk revolving between the poles of a small electromagnet in the circuit, and actuating a throttle-valve by means of a spring and a cone gearing. It was figured in the earlier editions of this work.

One great advantage of the electric governor is that it cuts down the consumption of steam to the actual demands made upon the electric circuit, and prevents injury both to the dynamo and to the steam-engine.

Dynamometric Governing.—Another method of governing dynamos is too important to be omitted. The power transmitted along the shaft is the product of two factors, speed and torque. If ω stands for the angular velocity and T for the torque, then

$$\omega \, T = \text{mechanical power in the armature.}$$

But the activity, or work per second, or power, of a dynamo can be measured electrically, by the product of its electromotive-force into the current it drives through the circuit. If E stands for the electromotive-force, and i for the current, then

$$E \, i = \text{electric power (gross) in the armature.}$$

In a good dynamo the electric power, though not equal to the mechanical power, will exceed 95 per cent. of it. Now we know that, other things being equal, the electromotive-force E of a dynamo is proportional to speed of driving. It follows at once that *the torque will be proportional to the current i.* This at once suggests that a dynamo may be driven so as to give a constant current, provided it be driven from a steam-engine governed *not by a centrifugal governor to maintain a constant speed*, but by *a dynamometric governor to maintain a constant torque or turning moment.* Some good transmission dynamometer, such as that of Morin, or one of the later varieties, such as those designed by Ayrton and Perry, or best of all that designed by the Rev. F. J. Smith,[1] may be adapted to work an equilibrium valve, and would fulfil the above condition of governing.

Prof. E. Thomson has suggested the use of a dynamometric apparatus to govern a constant-current dynamo by the method of shifting the brushes. A description of this governor was given in the second edition of this work.

Governing by Steam-Pressure.—It was remarked above that electric power and mechanical power are each a product of two factors. But in an ordinary steam-engine the work per second also consists of two factors, viz., speed of piston and steam-pressure; and the angular velocity of the shaft is proportional to the former, and its transmitted torque to the latter. Therefore the condition of maintaining a constant current ought to be fulfilled if the pressure is always constant. If the valves are such as to admit a fixed quantity of steam at each stroke, and if the boiler pressure is really kept up, then the average pressure behind the piston ought to be constant. In practice this is never attained on account of the friction of the steam against the steam-pipes and port-holes of the valves. The internal friction in the engine plays the same part in preventing absolutely true self-regulation, as does the internal electrical resistance in the dynamo. An approximation is all that is possible.[1] In an experiment made by M. Pollard with a Gramme dynamo, the current gave deflections on a galvanometer, varying only from 59° to 54°, while additional resistances were introduced into the circuit, which caused the speed to run up from 436 to 726 revolutions per minute. Theoretically, therefore, a constant current ought to be one of the easiest things to maintain with a series dynamo. Have adequate boilers, keep the steam-pressure always at one point, abandon all governors, and admit equal quantities of steam at each stroke whatever the speed; the result *ought* to be a constant current. The condition of maintaining a constant potential cannot be similarly solved, except by employing a shunt dynamo under conditions that are both uneconomical and impracticable. But in the case of constant-current work it is possible to go further toward realizing such results. The existing method of maintaining a constant steam-pressure is to put upon the boiler a pressure-gauge which indicates to the stoker when he is to add more fuel and when to damp down the fire. Let the pressure-gauge be abandoned, and instead, let there be provided at the side of the furnace an amperemeter, and let the stoker feed or damp his furnace fires according to the requirements of the electric system of distribution. Is there any valid reason why such a method of government should not be efficient in practice, at least in the case of the series dynamo for constant currents?

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[1] See his excellent little book on *Work-measuring Machines*, published by Messrs. E. and F. N. Spon.

Finally, to render the system truly automatic, it is conceivable that mechanical stoking appliances might be arranged, under the control of the amperemeter or voltmeter, to supply the fuel in proportion to the number of lamps alight.

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[1] See Edmunds in *Journal Soc. Telegr. Engineers*, xvii. 697, 1888; also *The Electrician*, xxii. 349, 422, 1889.

CHAPTER XXVIII.

TESTING DYNAMOS AND MOTORS.

Tests to be applied to dynamos are of two kinds , viz. those which relate to the design and construction of the machines, and those which relate to their performance. Under the former are included tests of the resistance of the various coils and connexions, and of the insulation of the working parts. Under the latter are comprised the tests of efficiency under various loads, and of output at different speeds and conditions of working.

Testing Construction.—The resistance of the various parts of the armature coils, of the field-magnet coils, and of the various connexions, may be tested in the ordinary manner, by means of a Wheatstone's bridge, or by one of the recognized galvanometer methods. The only point of difficulty lies in measuring such small resistances as those of armatures and of series coils, which are often very small fractions of an ohm. In this case probably the best method of proceeding is the following. By means of a few cells of accumulators send a strong current through the coil or armature whose resistance is to be measured, interposing in the circuit an amperemeter. While this current is passing, measure, by means of a sensitive voltmeter, the fall of potential between the two ends of the coil. By Ohm's law, the number of volts of fall of potential divided by the number of amperes of current will give the resistance in ohms. Additional accuracy may be secured by connecting in the circuit a strip of stout German silver, as recommended by Lord Rayleigh, of known resistance, and comparing the fall of potential between the two ends of the strip with the fall of potential in the coil. The ratio of the two falls of potential will equal the ratio of the resistances.

It ought on no account to be forgotten that the internal resistance of a dynamo when warm after working for a few hours is considerably higher than when it is cold. Tests of resistance ought therefore to be made both before and after the dynamo has been running. The perfection of the magnetic circuit may be tested in two ways. If the design or construction of the magnetic circuit is such as to give rise to magnetic leakage, it is desirable to ascertain the proportion of leakage. The actual amount of magnetic leakage may be measured by placing exploring coils over different parts of the magnetic circuit in the manner used by J. and E. Hopkinson. They passed a single convolution of wire around the magnet-frame at different points, and joined it to a suitable galvanometer. The throw imparted to the galvanometer when the current in the magnetizing coil was suddenly turned off or on, is a measure of the number of magnetic lines enclosed by the exploring coil. The other way of examining the perfection of the magnetic circuit is to join up a known suitable resistance to the terminals of the machine, and then to run it at a slow speed, gradually increasing the number of revolutions until it excites itself. (The method is of course inapplicable to many alternate-current machines.) The least speed of self-excitation is, *cæteris paribus*, a measure of the goodness of the magnetic circuit.

Testing Insulation-Resistance.—It was formerly the fashion to test the insulation-resistance between the coils of a dynamo and its metal cores or frame by using a Wheatstone's bridge and a couple of small cells. The results were supposed to be good if the test came out at a million ohms or more. All such tests are fallacious, as they afford not the slightest evidence as to whether the insulation is likely to break down under the working electric pressures. It must not be forgotten that the electric tension or stress to which the dielectric is subjected, tending to pierce it, varies as the square of the volts. The only rational mode of testing the insulation is to apply a high voltage—say from 2000 to 4000 volts—and see whether the insulation resists being pierced. The most convenient way of applying the test is to use a small alternate-current transformer, giving the requisite voltage. All dynamos, motors, and transformers intended for high voltage work should be tested at double the volts which they are intended to work at. All tests should be made when the apparatus is warm after having been used.

Testing Performance and Efficiency.—The testing of the efficiency and working capacity of a dynamo, whether working as generator or as motor, is a more serious matter, and involves both electrical and dynamometrical measurements.

In the case of the dynamo-generating currents, measurements must be made (*a*) of the horse-power expended, and (*b*) of the energy of the electric currents realized.

In the case of the motor doing work, measurements must be made (*a*) of the electric energy consumed, and (*b*) of the mechanical horse-power realized.

Measurement of Horse-power.—There are four general methods of measuring mechanical power:—

(*a.*) *Indicator Method.*—By taking an indicator diagram from the steam-engine which supplies the power.

(*b.*) *Brake Method.*—By absorbing the power delivered by the machine, at a friction brake such as that of Prony, Poncelet, Appold, Raffard, or Froude.

(*c.*) *Dynamometer Method.*—By measuring in a transmission dynamometer or ergometer, such as that of Morin, von Hefner-Alteneck, Ayrton and Perry, or of F. J. Smith, the actual mechanical power of the shaft or belt.

(*d.*) *Balance Method.*—By balancing the dynamo or motor on its own pivots and making it into its own ergometer.

To these must now be added a fifth method, namely:—

(*e.*) *Electrical Method.*—By making the motor drive the dynamo which supplies it, measuring electrically the work given out in the one, or absorbed by the other, and then measuring, either mechanically or electrically, the difference.

(*a.*) *Indicator Method.*—The operation of taking an indicator diagram of the work of a steam-engine is too well known to engineers to need more than a passing reference. This method is, however, not always applicable, for in many cases the steam-engine has to drive other machinery, and heavy shafting for other machinery. In such cases the only remedy is to take two sets of indicator diagrams, one when the dynamo is at work, the other when the dynamo is thrown out of gear, the difference being assumed to represent the horse-power absorbed by the dynamo.

(*b.*) *Brake Method.*—The friction-brake of Prony is well known to engineers, but the same can hardly be said of the more recent forms of friction dynamometers. Various improvements have been introduced in detail from time to time by Poncelet, Appold, and Deprez. In Prony's method the work is measured by clamping a pair of wooden jaws round a pulley on the shaft; the torque on the jaws being measured directly by hanging weights on a projecting arm with a sufficient moment to prevent rotation. If p is the weight which at distance l from the centre balances the tendency to turn, the the friction-force f multiplied by the radius r of the pulley will equal p multiplied by l.

This may be written,

$$\text{Torque} = f\,r = p\,l.$$

From which it follows that

$$f = \frac{p\,l}{r}.$$

If n be the number of revolutions *per second*, then $2\,\pi\,n$ is the number of radians per second, or in other words, the angular velocity for which we use the symbol ω, and $2\,\pi\,n\,r$ is the linear velocity v at the circumference. Now the work per second, or power, is the product of the force at the circumference into the velocity at the circumference, or

$$w = f\,v = \frac{p\,l}{r} . \, 2\,\pi\,n\,r = 2\,\pi\,n\,p\,l.$$

If p is measured in pounds weight, and l in feet, then, remembering that 550 foot-pounds per second go to one horse-power, we have

$$\text{Horse-power absorbed} = \frac{2\,\pi\,n\,p\,l}{550};$$

or, if p is expressed in grammes weight, and l in centimetres, it must be divided by $7{\cdot}6 \times 10^6$ to bring it to horse-power.

The later improvements imported into the Prony brake are of great importance. Poncelet added a rigid rod at right angles to the lever, and attached the weights at the lower end. Appold substituted for the wooden jaws a steel strap, giving a more equable friction, and therefore having less tendency to vibration. Raffard[1] substituted a belt differing in breadth, and therefore offering a variable coefficient of friction, according to the amount wrapped round the pulley. Further modifications of this kind of brake dynamometer have been made by Professor James Thomson, Professor Unwin, M. Carpentier, and by Professors Ayrton and Perry. The friction of a turbine wheel was also applied as a dynamometer brake by the late W. Froude.

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[1] For further accounts of these instruments the reader is referred to Weisbach's *Mechanics of Engineering*; Spons' *Dictionary of Engineering*, Article "Dynamometer"; Smith's *Work-measuring Machines*; a series of articles in the *Electrician*, 1883–4, by Mr. Gisbert Kapp; *Proc. Inst. Mech. Eng.*, 1877, p. 237 (Mr. Froude); *Rep. Brit. Assoc.*, 1883 (Prof.

As all these brake dynamometers measure the work by destroying it, it will be seen that though they are admirably adapted to measure the work furnished by a motor, they cannot, except indirectly, be applied to measure the work supplied to a dynamo. Some experience in working with these machines is essential if reliable results are to be obtained; but with the more modern forms of instrument, such as those of Poncelet and Raffard, the results are very good. The great secret of success is to keep the friction surfaces well lubricated with an abundant supply of soap and water.

(*c.*) *Dynamometer Method.*—The Prony brake was styled above a brake dynamometer; but the true dynamometer for measuring transmitted power does not destroy the power which it measures. Transmission dynamometers may be divided into two closely allied categories: those which measure the power transmitted along a belt, and those which measure power transmitted by a shaft.

In the case of transmitting power by a belt, the actual force which drives is the difference between the pull in the two parts of the belt. If F' is the pull in the slack part of the belt before reaching the driven pulley, and F the pull in the tight part of the belt after leaving the driven pulley, then $F - F'$ represents the nett pull at the circumference, and $(F - F') \times r$ is the torque T. Then if n is the number of revolutions *per second*, the angular velocity ω will be equal to $2 \pi n$. This gives us as the work per second, or power,

$$w = \omega T = f v = 2 \pi n r (F - F').$$

As before, if F is expressed in pounds weight and r in feet, the expression must be divided by 550 to bring to horse-power: or must be divided by $7 \cdot 6 \times 10^6$ if the quantities are expressed in grammes weight and centimetres.

A dynamometer which can be applied to a driving belt, and

Unwin); *Journ. Soc. Telegr.-Eng. and Electr.*, xlix., vol. xii. 346 (Profs. Ayrton and Perry).

actually measures the difference F – F′ in the tight and slack parts of the belt, has been designed by von Hefner-Alteneck, and is commonly known as Siemens' dynamometer.[1] Other forms have been devised by Sir F. J. Bramwell, W. P. Tatham,[2] W. Froude, T. A. Edison, and others. Nearly all of these instruments introduce additional pulleys into the transmitting system, causing additional friction.

Much more satisfactory are those transmission dynamometers which measure the power transmitted by a shaft. In nearly all instruments of this class there is a fixed pulley keyed to the shaft, and beside it a loose pulley connected with it by some kind of spring arrangement, so set that the elongation or bending of the spring measures the angular advance of the one pulley relatively to the other; this angular advance is proportional to the transmitted torque. To this class of instrument belongs the well-known dynamometer of Morin, in which the displacement of the loose pulley is resisted by a straight bar spring, the centre of which is attached to the driving shaft. Modifications of the Morin instrument have been devised by Easton and Anderson, Heinrichs,[3] Ayrton and Perry,[4] Murray,[5] and the Rev. F. J. Smith, of the Millard Engineering Laboratory, Oxford. Of the last-named instrument, a full description and cut were given in the former editions of this book.

(*d.*) *Balance Method.*—The following method was devised by Mr. Smith when testing some small Trouvé motors at the Paris Exposition of 1881. With small motors there arises the difficulty that the ordinary means of measuring the work they perform introduce relatively large amounts of extraneous friction. The motor to be tested is placed with its armature spindle between centres, or on friction wheels, and the weight of the field-magnets and frame is very carefully balanced with counterpoise weights. In Fig. 494, B D represents the field-magnets and frame of the motor duly counterpoised, and E is the armature. When the current is turned on, the armature tends to rotate in one direction, and the field-magnets in the other; the angular reaction being of course equal to the angular action. If the reaction which tends to drive the field-magnets round, be balanced by applying a force P (for example that of a spring balance) at the point C of the frame A B C D, then the moment of this force $P d$ measures the torque, exactly as in the Prony brake. Hence it will be seen that the motor has become its own dynamometer, the magnetic friction between the armature and the field magnet being substituted for the mechanical friction between the pulley and the jaws. A modification of the balance method, due to Herman Müller, consists in swinging the dynamo in a cradle, pendulum fashion, from the driving shaft, and estimating the power absorbed by the displacement from the vertical line.

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[1] One form of the Siemens dynamometer is described by Hopkinson, *Proc. Inst. Mech. Eng.*, 1879. A more modern form is described by Schröter, *Bayerisches Industrie-und-Gewerbeblatt*, 1883.

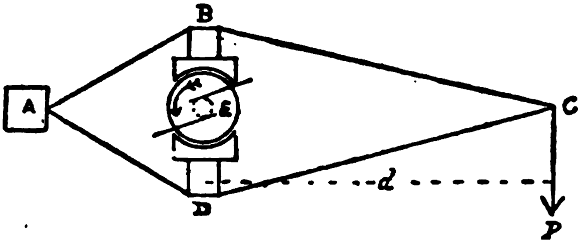
[2] *Journ. Franklin Institute*, Nov. 1886.

[3] See *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884, for an excellent account of a series of tests carried out with great care and ability for Mr. Heinrichs, by Messrs. Alabaster, Gatehouse and Co.

[4] *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 163, 1883.

[5] *Ibid.*, xviii. 1889.

FIG. 494.



SMITH'S METHOD OF TESTING MOTORS.

M. Marcel Deprez and Professor C. F. Brackett have proposed to apply the balance method to dynamos in action. Professor Brackett places the dynamo in a sort of cradle, balanced on centres that lie in the axis of rotation, and measures the angular reaction-force or torque between the armature and field-magnets, and multiplying this by the angular velocity $2 \pi n$, obtains the value of the power transmitted to the armature.

All these several dynamometric methods necessitate the use of a speed indicator to count the number of revolutions n, which enters as a factor into the calculation of horse-power. Too great care cannot be taken, especially in testing *small* machines, that no unnecessary friction be thereby introduced. A flexible connexion, such as a piece of dentist's spring, between the axle of the machine and the axle of the counter appears to be desirable. The number of revolutions *per second* n being known, the angular velocity $\omega = 2 \pi n$ can be calculated. This only requires to be multiplied by the torque T = F r to give the power of work-per-second w. And if T is expressed in pound-feet, then,

$$\text{Horse-power} = \frac{2\,\pi\,n\,F\,r}{550} = \frac{\omega\,T}{550}.$$

(*e.*) *Electrical Methods.*—There are several varieties of this modern method of testing, and they involve the use of two, or in some cases three machines. J. and E. Hopkinson[1] propose to use two similar machines, one as generator, the other as motor, connected together both electrically and mechanically. The power given out by the former machine, and that absorbed by the latter, are measured electrically. The motor is made to use its mechanical power to aid in driving the generator, and the small additional power required to drive the generator (supplied by a steam-engine) is measured mechanically by a dynamometer. Modifications of this method for the purpose of obviating all mechanical measurements have been suggested by Lord Rayleigh,[2] Captain Cardew,[3] whose method dates from 1885, M. Menges,[4] Mr. Ravenshaw,[5] Mr. Swinburne, and Mr. Kapp.[6]

All these methods are far more accurate than the rough mechanical methods of earlier date, and each has its advantages, but Hopkinson's method requires two similar machines, and Cardew's requires three machines, one of which must be powerful enough to run the other two. In Swinburne's method the loss of power due to resistance of conductors is calculated, and this deducted from the whole loss of power in the machine gives the "stray power" made up of losses due to eddy-currents, friction, and magnetic hysteresis, which are thus measured together. This stray power is determined by using the machine as a motor, the field-magnets being separately excited so that the armature has the same magnetic induction as at full load, the electromotive-force applied to it being such as to drive it at its normal speed. Only a small generating dynamo is required to furnish the current for this. When matters are so arranged that the machine to be tested runs at its normal speed, the power used in driving the machine (which is measured electrically by taking readings of the volts on the armature and the amperes flowing through it, and multiplying up) is equal to the stray power at full load.

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[1] *Phil. Trans.*, 1886, ii. 347. See also *Electrician*, xvi. 347, 1886; and *Electrical Review*, xviii. 207 and 230, 1886.

[2] *Electrical Review*, xviii. 242, 1886.

[3] *Ibid.*, xix. 464, 1886; and *Electrician*, xvii. 410, 1886; and xxi. 275, 1887.

[4] *Electrician*, xvi. 371, 1886.

[5] *Electrical Review*, xix. 424 and 437, 1886.

[6] *Ibid.*, xxi. 181 and 215, 1887.

An example may be useful. Suppose we have to test a large 50 kilowatt shunt-wound dynamo, giving 500 amperes at 100 volts at 720 revolutions per minute, and that $r_a = 0{\cdot}006$ ohm, and $r_s = 12$ ohms, the lost amperes will be $100 \div 12 = 8{\cdot}5$. total current say 508 amperes; hence lost volts $508 \times 0{\cdot}006 = 3$ volts; whence $E = 103$ volts. Watts lost in armature $= 508 \times 508 \times 0{\cdot}006 = 1548$. Watts lost in shunt coil $= 100 \times 100 \div 12 = 833$. Now arrange any small dynamo, of say 2 H P., to give out current at 103 volts: and from this run the large dynamo that is to be tested, as a motor, with no other load than its own friction, hysteresis and eddy-currents. It will run under 720 revolutions, since with such small current its armature produces no demagnetizing action to quicken it up. Therefore add some resistance to its shunt till it comes up to speed. Then measure the current it is taking; this multiplied by E gives the stray power. Suppose it takes 9 amperes, then the stray power is $103 \times 9 = 927$ watts. We may at once reckon out the efficiencies. The losses now known are $1548 + 833 + 927 = 3308$. Add this to the 50,000 watts of nett out-put, and we get the gross out-put 533.08. Hence we have the following:—

$$\text{Gross efficiency} = \frac{52381}{53308} = 98{\cdot}3 \text{ per cent.}$$

$$\text{Electrical efficiency} = \frac{50000}{52381} = 95{\cdot}5 \quad ,,$$

$$\text{Nett efficiency} = \frac{50000}{53308} = 93{\cdot}8 \quad ,,$$

Testing Separate Losses.—In the preceding paragraph no distinction was made between the three sources of loss which go to make up the stray power, namely, friction, eddy-currents, and hysteresis. It was indeed possible to separate the eddy-current loss from the others by making experiments at different speeds,[1] because the eddy-current loss increases proportionately to the square of the speed, whilst the other losses are approximately proportional simply to the speed. The power thus wasted was given to the armature by a motor, and measured electrically. In 1891 a method of separating these losses was independently published by Kapp[2] and by

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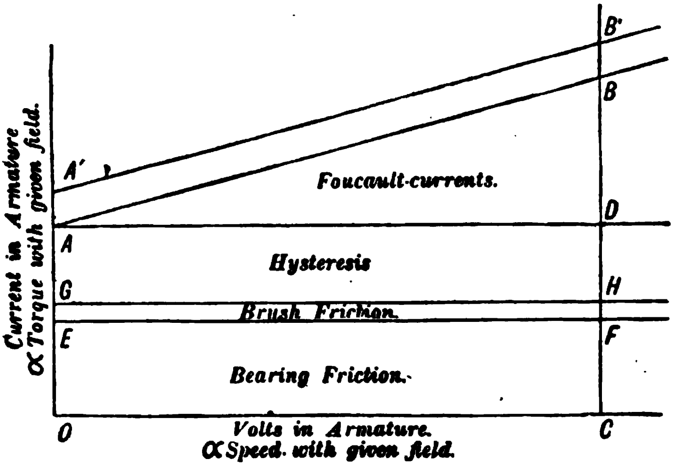
[1] *Journ. Inst. Electrical Engineers*, xviii. 620, 1889.

[2] *The Electrician*, xxvi. 699, 1891.

Housman.[1] From the latter's paper are taken Figs. 495 and 496, which show the method adopted by both these engineers. The method is as follows :—Let the field-magnet be separately excited to a constant value. Then measure the currents required to run the armature as a motor with no load at different speeds, by using different volts. The results when plotted out as a curve give a straight line A B, Fig. 495 cutting the axis of current above the origin. A horizontal line, A D, through A, divides the ordinates, such as C B, into two parts ; one C D, which represents the losses that are proportional to speed ; and another D B which represents those that are proportional to the square of the speed. To separate friction of bearings and brushes, the armature should be coupled direct to another similar machine, the latter running without excitation of magnets, when the increase of current needed to drive will give a measure of frictional loss, and from this the lines E F and G H may be plotted out. If a second set of observations are made with a field of different strength, a second line A′ B′ will be obtained, which will be above or below A B, according to whether the change of field has

FIG. 495.



SEPARATION OF LOSSES IN DYNAMO.

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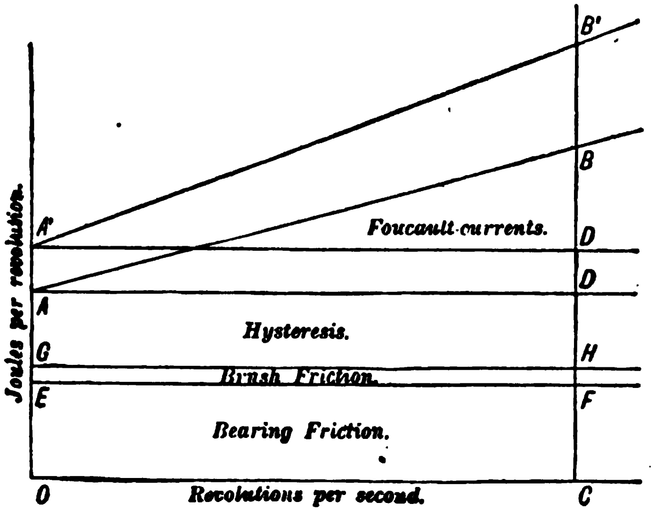
[1] *The Electrician*, xxvi. 700, 1891 ; also *Journ. Inst. Electrical Engineers*, xx. 298, 1891.

increased or diminished the total losses. The minimum total loss usually occurs with an excitation that makes B in the armature about 15,000 or 16,000; for when the excitation is pushed further, not only does hysteresis become much greater, but the eddy-currents in shaft and pulley, due to the leakage of magnetic lines, are greater. If the curve A B curves upwards at the higher values, it shows that the eddy-currents in the armature are producing perceptible demagnetization. In Fig. 496 the values plotted have been changed from electrical to mechanical values, so as to permit of a single scale being used for experiments with various degrees of excitation.

FIG. 496.



SEPARATION OF LOSSES IN DYNAMO.

Mr. Kapp has communicated to the author a method of testing which permits the commercial or nett efficiency to be determined electrically with far higher accuracy than is possible with any mechanical dynamometer. It requires two machines of nearly equal power, one to run as generator, the other as motor, together with a small auxiliary machine of normal voltage, to which the other two are coupled in parallel.

If the machine to be tested is called A, and its fellow B, we may call the small dynamo C. The armatures of A and B must also be coupled together mechanically, and the field of B must be weakened by use of a rheostat, so that it may run as a motor. C gives the current necessary for exciting and for making up the difference between the currents in A and B. Insert an amperemeter from one brush of A to one of B, to measure the current flowing from one to the other, and let two readings be taken when the current from C is introduced first at the terminals of A, then at those of B. The volts are the same in each case. Hence the ratio of the two currents is the efficiency of the combination of the two machines; and the square-root of the ratio of the two readings is the efficiency of either machine.

An elaborate arrangement of speed-cones for dynamo testing, designed by Prof. Ayrton, is described in *Industries*, June 22, 1888. For detailed account of tests on dynamos the reader is referred to the following sources :—*Report of Committee of Franklin Institution*, 1878 ; *Crystal Palace Exhibition* 1882, *Report*, by Lieut. F. J. Sprague, United States Commissioner; also see the Inaugural Address of Prof. W. G. Adams in *Journal Soc. Telegr.-Engin. and Electr.*, 1884; Thesis of J. W. Howell on tests made at Stevens Institute, reprinted in a volume on *Incandescent Electric Lighting*, published New York, 1883, by Messrs. Van Nostrand; *Official Report of Munich Electric Exhibition*, 1882; also the tests made by Messrs. Alabaster, Gatehouse and Co., reported in *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884; also *Report of Jurors, Cincinnati Industrial Exposition*, 1883; also Prof. W. G. Adams' Inaugural Address, *Journal of Society of Telegraph-Engineers and Electricians*, xiv. 4, 1885; also Reports of Electrical Exhibition at Philadelphia 1884, published in *Journal of the Franklin Institution*, 1884, tests of arc-lighting dynamo at Melbourne Exhibition, by R. L. Murray, *Journal Institution Electrical Engineers*, xviii., 1889; tests of dynamos (Desroziers, Edison, Gramme, &c.) at Paris Exhibition of 1889, by A. Minet, *La Lumiere Electrique*, xxxv., 1889 ; tests on Stanley Arc Alternator by Duncan and Hassen, *The Electrician*, xxvi., Jan. 1891; tests of a Goolden dynamo and Willans engine, separating the losses, *ib.* xxvi. 36, 1890; tests of a Wenstrom dynamo, separating the losses, by Duncan, *Electrical Review*, xxvi. 116, Jan. 1890; papers on Causes of Losses, by Hummel, in *Elektrotechnische Zeitschrift*, viii., 1887, and xii. 1891. At the Frankfort Exhibition of 1891, very careful tests were made of numerous machines under very favourable conditions. None of the results of these tests are yet available down to the hour of going to press.

CHAPTER XXIX.

MANAGEMENT OF DYNAMOS.

THIS chapter is devoted to three topics :—(1) The coupling of two or more dynamos ; (2) General instructions in use of dynamos ; (3) The diseases of dynamos.

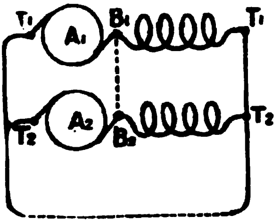
ON COUPLING TWO OR MORE DYNAMOS IN ONE CIRCUIT.

It is sometimes needful to couple two or more dynamos together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. Thus it may occur that two dynamos, neither of which can safely carry a greater current than 1000 amperes, are required to supply jointly a 2000-ampere-current : or two machines, each of which can run at 60 volts, are required to furnish an electromotive-force of 120 volts. Simple as these cases may seem, it is not so easy to carry them out, because it depends upon the construction of the machine, and especially upon the mode of excitation of the field-magnets, whether they can be coupled together without interfering with each other's running. For it may, and does, occur that if not rightly arranged, one machine will absorb energy from the other and be driven as a motor instead of adding anything to the energy of the circuit.

Coupling Machines in Series.—Series-wound dynamos may be united in series with one another for the purpose of doubling the electromotive-force. Thus two Brush machines, each working at 10 amperes, and each capable of working 6 arc-lamps, may be joined in one circuit with 12 arc-lamps in series. The only needful precaution is to see that the + terminal of one machine is joined to the - terminal of the other, precisely as with cells of a battery. Shunt-wound dynamos may also be coupled in series, though the arrangement is not good unless the two shunt coils are also put in series with one another, so as to form one long shunt across the circuit. Compound-wound dynamos may be connected in series with one another, provided the shunt parts of the two are connected as a single shunt, which may extend simply across the two armatures (double-short-shunt), or may be a shunt to the external circuit (double long-shunt), or may be a mixture of long and short shunt. The same considerations apply to more than two machines. The coupling of alternate-current dynamos is considered in Chapter XXII.

Coupling Dynamos in Parallel.—Two series dynamos cannot be coupled in parallel in a circuit without a slight re-arrangement, otherwise they interfere. For, suppose one of them to fall a little in speed, so that the electromotive-force of one machine is higher than that of the other machine with which it is in parallel, the machine having the higher electromotive-force will then drive a current in the wrong direction through the other machine, reversing the polarity of its field magnets and driving it as a motor. To obviate this, Gramme made the suggestion that the machines should be coupled in parallel at the brushes as well as at the terminals. This is shown in Fig. 497. The terminals T_1 T_1 of one machine are respectively joined to T_2 T_2 of the second machine, and a third wire joins B_1 with B_2. If both machines are doing precisely equal work, there will be no current through the wire B_1 B_2. If either machine falls behind, part of the current from the other machine will flow through B_1 B_2 and help to maintain the excitement of the magnets of the weaker machine. This effectually prevents reversals.

FIG. 497.



COUPLING OF TWO SERIES DYNAMOS IN PARALLEL.

In the case of shunt machines there is no great difficulty in running them in parallel, as indeed is done on a large scale every day in central lighting stations. The chief precaution to be taken is that, whenever an additional dynamo has to be switched into circuit, its field must be turned on, and it must be run at full speed before its armature is switched into connexion with the mains, otherwise the current from the mains will flow back through it and overpower the driving force.[1] Another method of coupling two series machines is to cause each to excite the other's field magnetism. This equalizes the work between the two machines.

Coupling of Compound Dynamos in Parallel Circuit.—In working compound dynamo machines in parallel circuit, some difficulty has been found, because if for any reason the current from any one machine increases the exaltation of the field strength in such a case, due to the increase of the current traversing the series circuit, raises the electromotive-force of the machine, and causes it not only to do more than its due share of the work, but even to send a back current through the machine which is connected with it, which on account of its reduced electromotive-force becomes merely a part of the external circuit of the more powerful generator. There is no doubt that such an action may take place; and if unavoidable would render compound dynamos unsuitable for employment in many situations where their self-regulating powers must render them very useful. Mr. Mordey first pointed out that the difficulty might be overcome by connecting the parallel machines in such a way that not only are the shunt portions of the field magnets in parallel circuit, but the series circuits of the field magnets are also a shunt on one another; in other words, by connecting the brushes, as well as the terminals, in parallel circuit, precisely as Gramme has done for series-wound machines. This mode of connexion is shown by the accompanying diagram (Fig. 498).

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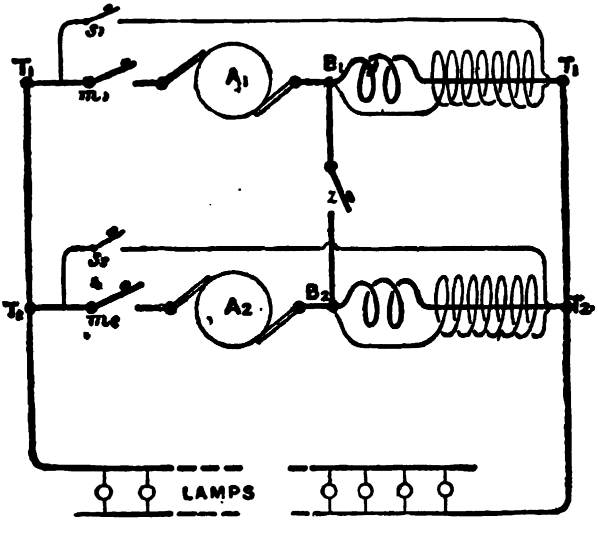
[1] See Burstyn, in the *Zeitschrift für angewandten Elektricitatslehre*, 1881, p. 339, also Schellen (2nd Edition), p. 717; Ledeboer, in *La Lumiere Electrique*, xxvi. 210, 1887; Meylan, in *La Lumiere Electrique*, xxvi. 379, 1887; and Feussner, in *Zeitschrift für Elektrotechnik* (1887), 108. See also the special mode devised by S. S. Wheeler, U. S. Patent, No. 335,048 of 1886.

FIG. 498.



COUPLING OF TWO COMPOUND DYNAMOS IN PARALLEL.

A_1 A_2 are the armatures of two compound dynamos, T_1 T_1 and

T_2 T_2 are the terminals ; the wire B_1 B_2 acting in conjunction with the lead T_1 T_2 on the left, puts the armatures in parallel. When compound dynamos are connected in this way,[1] they work quite satisfactorily, and exercise a considerable power of mutual adjustment. No necessity exists for driving by clutch or other positive connexion, ordinary belt driving being quite admissible, even when the belts have different percentages of slip—as may happen when they are not alike in tightness or character.

This mutual adjustment extends also to the case of slight differences in the sizes of the driving or driven pulleys where a single steam-engine or other motor is driving both or all of the machines, as well as to the case of separate engines being employed to drive separate machines. Of course the power of mutual adjustment must not be unduly strained by trusting to it to remedy inequalities of a serious nature.

The *rationale* of this adjustment is very simple. Taking the case of two exactly similar compound dynamos, connected as described above, it will be evident that as the shunt fields as well as the series fields are similar, and are respectively in parallel circuit, the strength of the magnetic fields in the two dynamos will be alike. Then at the same speed their electromotive-forces will be equal, and they will absorb power equally, and will do equal work. But if from any cause one of them begin ever so slightly to lag behind the other in speed, its electromotive-force will become slightly lower, and it will absorb proportionately less power. The power being thus unequally distributed, the slow machine will tend to race, while the fast one will tend to slow down. In this way the two dynamos will exercise a continual mutual adjustment, resulting in an equal division of the work between them.

And not only does this control exist with similar compound dynamos, but it may be relied on when the dynamos are unlike in size, power, and speed.

For instance, large and powerful machines may be worked in parallel circuit with smaller machines of various power, and each will do its proper share of the work.

In such a case, however, it is necessary to observe an additional precaution. Not only should the various dynamos be connected together, and to the external circuit, according to the plan described above, but such a proportion should be observed between the resistances of the series coils of the various connected machines that with the varying resistance of the external circuit the fall of potential in all the series coils may be similar. This is the case when the respective resistances of the series coils are inversely proportional to the full (or any equal proportion of the full) current intended to be generated by each dynamo.

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[1] The method proposed by M. Ledeboer in *La Lumière Electrique*, xxvi. 210, 1887, is practically identical with the above.

When the resistances of the series fields of the parallel dynamos are thus inversely proportional to their currents, they will work satisfactorily in parallel circuit, and will possess the desired power of adjustment under any circumstances likely to arise in practice where ordinary care and skill are exercised.

The examination of the subject does not, of course, cover all the details of the actions connected with the working of compound dynamos in parallel circuit. A fuller inquiry reveals a theoretical necessity for giving an exactly similar formation to the characteristic curves of all the connected machines. For practical purposes, however, the foregoing precautions will generally be found sufficient.

A method of connecting the machines, differing from the above, has been suggested. It is very similar to that which has been used, as mentioned above, with Gramme dynamos, consisting in employing the current of one machine A to excite the fields of a second machine B, while the current of B in turn is made to magnetize the fields of A. This is a perfectly practicable plan. With compound dynamos the series coils will alone require to be operated in this way. But there are some objections to such an arrangement. It can only be used when the dynamos are exact copies of each other, and is therefore out of the question when it is desired to utilize machines of various sizes and speeds to operate one circuit. Another objection is that with such a method it is always necessary to have at least two machines working, even when one is sufficient or more than sufficient for the requirements of the moment. In such a case, when it may be desired to use one machine only, an arrangement of switches, always more or less unsatisfactory, must be adopted; while the making of the involved change could scarcely be effected, while the machines were working, without causing some interruption to the external current—an event, however momentary, to be carefully avoided in practical work. Again, an accident to one machine would incapacitate not only that machine, but also the second one which relied on the former for its field excitation.

The plan suggested by Mr. Mordey appears the more satisfactory one, and may be used in a lighting station, or in any situation where the varying requirements of the circuit render it desirable to bring additional machines into operation as the work increases, and to disconnect them from the mains as the demand for current falls off. To accomplish this the following arrangements and order of operations should be observed. The dynamos should each be furnished (see Fig. 498) with a switch s in the shunt circuit; they should each have also a switch m in their main circuit between the armature part and the point where the shunt circuit joins on, so that the armature part may be interrupted without interrupting the shunt circuit. The connecting wire from brush to brush, which should be at least as thick as the mains, should also be furnished with a switch z. Suppose dynamo No. 1 is at work alone, its two switches, $s_1 m^1$, will be closed. If, now, dynamo No. 2 is to be thrown in, the following order must be observed. First get up the speed of No. 2 to its full value, then close s_2, then z; this will fully excite its magnetism; lastly, close m_2. When No. 2 has to be thrown out of circuit the order must be exactly reversed: first open m_2; then z; then s^2; lastly, slow down the machine. A special combination-switch, which will perform these successive operations in their proper order, is desirable.

The coupling of alternators has been specially considered in Chapter XXIII.

GENERAL INSTRUCTIONS IN USE OF DYNAMOS.

Position of Dynamo.—The place chosen should be dry, free from dust, and preferably where a cool current of air can be had. It should allow a sufficient room for a belt of proper length, unless the dynamo is direct-driven.

Foundations.—It is most important to secure good foundations for every dynamo; and if the dynamo is direct-driven, but is not on the same bed-plate as the engine, a foundation large enough for both together should be laid down. Stone or concrete may be used, or brick built with cement, having a large thick stone bedded at the top. For small dynamos the holding-down bolts may be set with lead or sulphur in holes in the stone top; but for large dynamos the bolts should be long enough to pass right down to the bottom, where they should be secured into iron plates built in. If long holes are left in the foundations for the holding-down bolts, they should be filled in with thin cement after the latter have been put in place.

Sliding Rails.—All belt-driven dynamos ought to be provided with tightening gear to take up the slack. If the dynamo is not provided with sliding rails under its bed-plate and tightening screws, the less desirable method of employing a tenting pulley, as in Plate XX., may be used. In any case the bed for dynamo must be quite level, and the shaft set properly parallel with the driving pulley.

Before Starting.—Examine the dynamo before it is set running for the first time. Remove caps of bearings and clean them and the journals. Replace them, but do not screw up too tightly. See that lubricators are filled, and the drip properly adjusted. Use *copper* oil-cans. Turn the armature round by hand to see that nothing catches, and no loose wires or waste are adhering to it. Clean up the commutator with the finest emery cloth, and note carefully that no dirt or copper-dust is lodged between the bars of the commutator. A stiff dry hog-brush will be useful here. See that the brush-holders work rightly, and that the hold-off catches, if any, are in order. See that each brush is properly trimmed (*i. e.* filed off at the proper bevel at the ends. Some makers provide a special tool to guide the file at the proper angle). Adjust the brushes, first, by clamping them *very firmly* in their holders, so that they protrude to the proper length. (For this purpose many makers provide each holder with a pointer, as at P on Plate III). Adjust them, secondly, so that they bear with a moderate but firm pressure on the commutator. See, thirdly, that when so pressing, they bear in the right positions. For two-pole dynamos the brushes should bear on precisely opposite bars of the commutator. For four-pole dynamos they bear on bars that are a quarter of the circumference apart. (It is customary for makers to mark two of the commutator bars with a centre-punch so that this adjustment may be verified). Then, having verified these adjustments, raise the brushes out of contact until they have started running. Wherever a single dynamo is driven from an engine it is well that the brushes should be only lowered after starting running, and raised before stopping running, so as to avoid all chance of the brushes being spoiled by the dynamo turning in the wrong direction. But the current should always be turned off before a brush is raised, otherwise a destructive spark will spoil the commutator.

The brushes being adjusted and lubricators filled, see that the connexions are right, the terminals tightly screwed down. Then begin running with brushes raised out of contact and main-switch open just to see that all is right mechanically, and that the bearings do not heat. Then let down the brushes. If the machine is shunt-wound it will at once excite itself, though the main-switch is still open. If the dynamo is for supplying glow-lamps, do not on any account turn on the main-switch until you see whether the machine is giving the right volts, or you may ruin all your lamps. For if the speed is too high, the volts may be too high. A pilot lamp or a voltmeter will tell you if all is right. Then, before you turn on the main-switch, observe the brushes to see if there is any sparking. If there is any sign of sparks, rock the brushes forward or backward till a sparkless place is found. Not until then should the main switch be turned and the lamps lit.

Daily Attention.—Beside daily lubrication, attention must be given to the brushes to see if they require to be fed forward or trimmed. The commutator should not be oiled, but only wiped with an oily rag or a piece of cotton cloth (*not* waste) smeared with vaseline. (This reservation does not apply to arc-light dynamos with special commutators with wide air-gaps like those of the Thomson-Houston machine, which may be oiled freely.) If the dynamo is driven from heavy shafting, so that there is no risk of turning backwards at starting or stopping, then the brushes may always be left down on the commutator. Many dynamos will spark at full load unless the brushes are rocked forward beyond the point that gave sparkless running on open circuit. Sparkless running is a vital matter if the commutator is to last long. The attendant cannot be too strongly impressed with the necessity of proper care on this matter. A well-designed modern dynamo, if properly attended to, will soon acquire a beautiful dark-polished surface on its commutator. But the commutator, even of a good machine, may be ruined in a few hours by careless or ignorant handling. If the brushes press too heavily, it will become scored or ploughed up. If they press too lightly, or if there is vibration that causes them to jump, or if they are allowed to spark, the commutator will be worn away in patches at the edges of some of the bars, and lose its cylindricity of outline. The only remedy in this case is to carefully turn it or file it down true; and this should occur very rarely.

DISEASES OF DYNAMOS.

At least four-fifths of the mishaps and break-downs that occur with dynamos arise from causes more strictly within the province of the engineer than in that of the electrician. On the other

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[1] See paper by the author in *The Electrician*, xx. 82, 1887; see also articles in *Electrotechnische Zeitschrift*, xi. 186, 1890; *Electrical World*, xiv. 99, 184, and xviii. 383, 1891.

hand, many of the mechanical faults that develop themselves in the machine might have been avoided had the engineer been possessed of a better knowledge of the electric and magnetic conditions which obtain in the running of the machine. It is not often nowadays that armatures fly to pieces. That disaster has seldom occurred since good engineers took in hand the construction of dynamos. The points which it is difficult for the ordinary engineer to grasp are the circumstance that it is on the copper conductors rather than on the iron core that the drag and stress of the magnetic field is exerted, and the necessity throughout of preserving proper insulation. All insulation being mechanically bad, he is apt, in attempting to give mechanical strength, to use the insulating materials in some way that vitiates their adequacy. For want of full electrical information he may apply the insulation in an erroneous manner and produce a dynamo which will break down under the severe conditions of actual work.

Burning-out of Armatures.—Single coils of an armature sometimes get heated to redness and burn the insulation. Sometimes a whole armature will become overheated, producing a general charring. The latter case happens more often to the armatures of motors than to those of dynamos. For if any excessive current is drawn by accident from a dynamo, the torque on the armature will generally become so great as to throw off the belt or pull up the engine. Whereas, with a motor, if the armature is jammed so that it cannot turn, an enormous current will continue to flow through it if the supply be not cut off. The burning of a single coil or section of the winding is sometimes due to short-circuiting at the commutator between two adjacent bars ; but more often it is due to short-circuiting in the armature itself. In drum armatures, and in those forms of ring armature which are so connected that the windings cross over one another, this evil may occur in consequence of the abrasion of the insulation. In the old wire-wound drum armatures short-circuits were frequent, from the overwrapping of the ends of coils of widely-different potentials. Short-circuit between an imperfectly insulated wire and the iron core beneath it is again a fruitful source of trouble. Not that any *one* such contact can of itself produce any effect : but that if there is one such contact, then, if a fault occurs anywhere in the lamp circuit, there will at once be developed a serious leak through earth. Also the risk of shock to persons casually touching any part of the circuit is greater if there is any single fault in the dynamo. Some firms—chiefly American[1]—prescribe that the dynamo frame itself should be insulated from the ground. This is an absurdity for any dynamos except those working at high voltage. The author's experience leads him, on the other hand, to prescribe that the framework of the dynamo should, on the contrary, be carefully connected to earth. If this is done, the risk of accident to attendants—which is considerable in the case of high-voltage machines insulated from their bed—is reduced to a minimum. A contact between an armature conductor and the iron core may occur because of the iron laminæ becoming loose and wearing through the layers of insulation. If the insulation is not waterproof and has got wet, it may break down when the machine is run. Sometimes armatures are destroyed by the burning of the insulation, by the overheating, not of the conductors, but of the iron core. In such cases either the core has not been properly laminated, or else the insulation between the core-discs is defective. The burning of binding wires, which occasionally occurs, is due to want of compliance with the sufficient and necessary electrical conditions. Mica alone, in slips, under the binding wires is insufficient, as it is apt to be slowly ground to powder. It should be placed between strips of some other material, such as vulcanized fibre, as a mechanical backing.

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[1] The lightning arresters used on many dynamos in the States are them-

Being pieces of running machinery, dynamos are liable, as all engines are, to heating of bearings, if proper attention is not paid to lubrication and to the avoidance of needless dirt.

Fracture of Connexions.—This most annoying fault—the fracture of the connecting pieces which lead down from the armature conductors to the bars of the commutator—appears to be partly mechanical and partly electrical. These connecting pieces pass through a partial magnetic field, and they carry at times strong currents, which are reversed twice in each revolution. Hence they are each racked by lateral forces as they rotate, and this incessantly repeated breaks them off at last. The cure is either to make them mechanically very strong, or of stranded material, or to arrange that they shall lie outside the waste field.

Disconnexions in Armature.—Sometimes a disconnexion occurs where the armature conductors or windings are coupled up or connected down to the commutator. The evidence of this is (i) a sparking that cannot be stopped by rocking the brushes for-

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selves a source of mishaps. If the dynamo frame is properly earthed there is no need of a lightning arrester on the dynamo. Efficient lightning arresters should be fixed outside the dynamo-house where the overhead circuit enters it.

ward or backward, and (ii) one or more of the bars of the commutator appearing as if burned at the edge. One way[1] of finding the location of such a fault is to run the dynamos on open circuit, that is to say, with the brushes down, but no lamps on. Then after a few minutes' run stop the machine and see if any of the joints of the connectors are hot; this will indicate a partial disconnexion. If any entire coil is found to be hot, that is evidence not of a disconnexion, but of a short-circuit.

Flats in the Commutator.—Occasionally one of the commutator segments will become burned away or worn down to a lower level than the rest, or two adjacent bars may be similarly affected, causing a flat part on the cylindrical surface. Various suggestions have been offered to explain the origin of flats. If one of the bars was of unusually soft copper it might wear away faster; but the occurrence is unlikely. A partial disconnexion in the armature at the part connected to the particular bar of the commutator will give rise to a spark here at every half-revolution, so biting away this bar. Flats have been noticed also to spread along the bar from a flaw at one spot.

Another undoubted cause of flats is a mechanically weak or defective means of driving. If an armature, attached by a three-legged spider, is mounted on a weak shaft that bends, it is possible that periodic vibrations may occur which will cause the brushes to jump and set up sparks at definite points around the commutator. With well-constructed armatures, well-balanced and running without vibration, there is little fear of flats if the pressure of the brushes is sufficient. Whenever a bar of the commutator shows signs of burning along its edge, steps should at once be taken to prevent the development of a flat. A fine file should be applied to smooth the surface of the commutator in the neighbourhood of the threatened spot. Or, if need be, the commutator should be very slightly turned down. A narrow tool should be used for this purpose, so as not to drag the copper, and the surface should be polished with very fine emery cloth and examined to see that at no spot has the thin strip of mica been bridged over by a burr at the edge of any of the bars.

Faults in Field-magnet Coils.—Sometimes faults occur in field-magnet coils. These may be of two kinds—disconnexions or short-circuits. When there is a disconnexion the machine will probably refuse to excite itself. To make sure, the suspected coil should be disconnected at the ends and tested. A cell of Leclanche battery and a simple detector galvanometer, or, failing this, a common electric bell will suffice to prove whether the wire is continuous. If the frames on which the coils are wound are loose, the resulting vibration may cause the leading-out ends of the wires to snap, perhaps at some point below the surface which can only be reached by unwinding the coil. A short-circuit between any two of the windings will have the effect of keeping the short-circuited part cool whilst the rest of the coils are hot. In a shunt coil, short-circuiting some of the windings causes the rest to overheat dangerously. A short-circuit may arise between the frames or cores and the coils, and may be also tested for by electric bell or detector as above. If there is a single contact fault of this sort between coils and iron-work in the field-magnet, then a single fault at any other point—armature, commutator, brushes, terminals, or circuit—may work dire disaster. Once the author was confronted by a curious double fault which for some time defied detection. In a small Brush arc-light dynamo two single faults occurred at the screws which fixed the iron support that held the rocker for one of the pairs of brushes, with the result that two of the four pairs of coils on the armature were short-circuited.

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[1] Another way, applicable only to drum amatures, is due to Loomis (*Electrical Engineer*, New York, December 1891), and consists in holding the armature by hand and slowly turning it round against the torque while supplied with a current from some external source. If a position is found where it is easier to turn, it is clear that in this position the disconnexion stops part of the current, so that the fault can at once be found by tracing the connectors which run from those bars of the commutator which are at the brushes in this position.

Faults of Alternators.—Alternators are liable to faults of special kinds. Sometimes they show a regular pulsating flicker, timed exactly to the revolutions of the armature. This can only be due to some double inequality. If one pair of poles of the field-magnet is weaker than the rest, and one of the armature coils is defective, then when these come together in position once in each revolution the current may show a momentary drop. Alternators are usually made for high voltage, and are therefore liable to faults of insulation that might not occur in low-voltage machines. If the two collecting rings are side by side on the shaft, a spark—or rather arc—may spring over from one to the other unless a high projecting washer of ebonite is interposed. The peculiar racking action of the alternating current on the armature coils (see p. 638) is responsible for many failures in this class of machine.

Obscure Causes of Mishap.—Occasionally it occurs that a dynamo fails to give any current. In all such cases the first thing to suspect is that a disconnexion of the circuits has occurred. All terminals and coupling screws should be examined, The lacquer under the head of a terminal screw—where no lacquer ought to be—may be responsible. Dirt between the brushes and their clamps, or between the brush-holder and the brush-holder rod, may be the cause. A shunt-dynamo will not excite its magnets if the main circuit is short-circuited; and a series-wound dynamo will not excite them if the main circuit is open. If all other expedients to get the machine to excite itself fail, try the effect of reversing the connexions that take the current from the brushes to the exciting coils.

Many a mishap has been caused by too free a use of oil, or by oil leaking over from the bearings to the commutator or getting into the armature. Oil is apt to spoil the insulating materials by rotting the varnish, and affording a lodgment for dirt and for the fine copper dust that flies from the brushes. Also, if oil gets to the commutator it will char under the brushes, forming a carbonaceous film between the commutator bars, inviting a short-circuit. This fault is less likely to occur when mica-insulation is used than when asbestos or paper is employed. It has been observed that the brushes wear and heat unequally: the positive brush wearing faster than the negative. But this is unimportant. If there is solder on the brushes, care should be taken that the soldered part should never be used for contact on the commutator: it will set up flashing sparks.

Vibration and Noise.—Excessive vibration can only be due to want of proper balance in the armature. Vibration of a kind that may, nevertheless, be disastrous to the dynamo, racking its conductors, pounding its insulation to dust and causing the brushes to jump and spark, may be occasioned, even in a well-balanced machine, if it is not firmly secured to a proper foundation. Continuous-current machines should run practically silently: the belt will make far more noise than any part of the dynamo, Alternators do not usually run silently, for the coils of all disk armatures churn the air between the poles. If the iron cores of the armature part are subjected to too severe a cycle of magnetization they will emit a loud humming sound, which cannot be cured except by using the machine at a lower degree of excitation, being a defect of design. Once the author came across a remarkable case of an alternator which emitted a sustained howling sound of piercing loudness. The cause in this case was the accidental coincidence between the number of alternations and the natural vibration period of some of the solid iron parts. It was cured by re-fitting the iron parts so as to alter the fulcrum from which the parts could vibrate.

APPENDIX A.

ELECTRIC AND MAGNETIC UNITS.

THE principal units employed by practical electricians, by international agreement, are:—

The *ampere*, or unit of current (formerly called the *weber*);

The *volt*, or unit of electromotive-force.

The *ohm*, or unit of electric resistance.

These three practical units are based upon certain abstract units, derived by mathematical reasoning and experimentally proven laws, from the three fundamental units:—

The *centimetre*, as unit of length.

The *gramme*, as unit of mass.

The *second*, as unit of time.

The system of "absolute units" derived from these is often denominated the "C.G.S." system of units[1] to distinguish it from other systems based on other fundamental units.

Every system of measurement is based upon some experimental fact or law. We can only measure an electric current by the effects it produces. An electric current can (1) cause a deposition of metals from their chemical solutions; (2) heat the wire that it flows through; (3) attract (or repel) a parallel neighbouring current; (4) accumulate as an electric charge that can repel (or attract) a neighbouring charge of electricity; (5) produce in its neighbourhood a magnetic field, that is to say, can exert a force upon the pole of a magnet placed near it, as, for example, in galvanometers. Now any one of these effects *might have been* chosen as a basis for a system of units of measurement, and all of them have been proposed by one authority or another. As a matter of fact, the fifth of them is made the basis in the system now adopted by international agreement; and it is the best because, firstly, it connects the electrical units with the magnetic ones, and, secondly, it is closely connected with the mechanical units, enabling the mechanical values of the electrical quantities to be readily calculated.

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[1] The reader who may desire fuller information about the C.G.S. system of units is referred to Professor Everett's *Units and Physical Constants*.

Taking then the experimental fact that an electric current flowing in a wire can exert a force upon the pole of a magnet placed near it, we have next to define the conditions with the utmost precision. It is found by experiment that the force which is exerted upon the magnet-pole by the current depends on several other things beside the strength of the current: the force is proportional (*cœteris paribus*) (1) to the length of the conducting wire, (2) to the inverse square of the distance between an element of the wire and the pole, (3) to the strength of the magnet-pole. To be very precise then we ought to take (1) a wire one unit in length, (2) bent into an arc of unit radius so that each element of the wire is at unit distance from the pole, (3) and take a magnetic pole of one unit strength. If these things were done, and there was made to flow through the wire a current so strong that it acted on the pole with one unit of force, then a current of such a strength might be taken as a standard of comparison; for a current that was twice as strong would exert two units of force on the pole, and so forth. But in order to be exact we have yet to define what is meant by "one unit of force" and "a magnet-pole of one unit of strength." Here again we have to go to experimental facts, and choose such as will best suit for the purpose of making a consistent system of units.

A force must be measured by one of its effects, such, for example, as these: that it can (1) raise a given mass against the downward pull of the earth; (2) elongate a spring; (3) impart motion to a given mass, or in other words accelerate it. The first of these, which would seem the most natural to select, is rejected because the downward pull of the earth is different at different places, the second because it would acquire awkward definitions of the elastic properties of springs. So the third is chosen, and to make the definition precise, it must be remembered that experiment proves that the velocity of motion which a force imparts to a mass is proportional (1) to the force, (2) to the time during which it is applied, (3) inversely to the mass acted upon. If therefore, one could get such a force that, if it lasted one second and was made to act on one gramme, it imparted to that mass a velocity of one centimetre per second, then such a force ought to be called the unit of force. This unit has received the name of "one *dyne*." It may be remarked that the downward pull of the earth on a mass of one gramme is sufficient to give it at the end of one second a velocity of about 32 feet per second, or, more exactly, 981 centimetres per second (in the latitude of London); hence it is clear that the pull of the earth on one gramme (what is commonly called the gramme's weight) is equal (at London) to 981 dynes. The pull of the earth on a pound (commonly called the pound's weight) is 444,971 dynes (at London). A pound at the Pole would weigh 445,879, and at the Equator only 443,611 dynes. One dyne is a pull equal to 0·0157, or about $\frac{1}{63}$ of the weight of a grain (at London). Now, as to the unit strength of the magnet-pole or unit of magnetism: a magnet-pole can (1) lift a piece of iron; (2) repel (or attract) another magnet-pole at a distance. The first of these two effects is rejected as a basis for a definition of a unit because the load that a magnet-pole will lift does not depend only on the amount of magnetism at the pole, but on the shape and quality of the piece of iron lifted. For precise definition of the second effect, upon which the definition is based, it must be remembered that experiment has shown that the repulsion of one magnet-pole by another is proportional (1) to the product of the strengths of the two poles, (2) inversely to the square of the distance between them. If, therefore, we choose two similar and equal poles of just such a strength that when placed at unit distance apart they repel each other with unit force, then such poles will possess that amount of magnetism that ought to be called the unit quantity of magnetism.

We may now retrace our steps and build up systematically the units of the C.G.S. system.

The absolute unit of force ("dyne") is that force which, if it acts on one gramme for one second, gives to it a velocity of one centimetre per second.

The unit of magnetism, or unit magnet-pole, is one of such a strength that when placed at a distance of one centimetre (in air) from a similar pole of equal strength it repels it with a force of one dyne.

The absolute unit of current is one of such a strength that when one centimetre length of its circuit is bent into an arc of one centimetre radius, the current in it exerts a force of one dyne on a unit magnet-pole placed at the centre.

The last definition is difficult to realize in practice, and a complete circle of one centimetre radius is more easy to work with than an arc of one centimetre long only. If the radius be more than one centimetre and there be more than one turn of wire, as in most tangent galvanometers, then a formula is necessary.

Writing r for the number of centimetres of the radius, the length of circumference will be equal to $2\pi r$. Then writing S for the number of turns of wire in the coil, and i for the strength in absolute units of the current, the formula connecting these with the force (in dynes) exerted by the current on a unit pole at the centre is:—

$$\frac{2\pi r S i}{r^2} = f;$$

whence

$$\frac{2\pi S i}{r} = f.$$

In the case of the tangent galvanometer, the force, instead of being measured directly is ascertained indirectly, by knowing the value (at the place of observation) of the horizontal component of the magnetic field due to the earth's magnetism, commonly represented by symbol H, and measuring the tangent of the deflexion produced on a magnetic needle hung at the centre when the coil lies parallel to the magnetic meridian. In this case $f = H \times \tan \delta$; whence

$$\frac{2\pi S i}{r} = H \tan \delta.$$

From this it follows that if S, r, H, and the tangent of deflexion are known, the strength of the current i will be reckoned by making the following calculation :—

$$i = \frac{r\,H}{2\pi S} \tan \delta.$$

(The value of H may be taken as 0·18 at London, and of the following values at other places :—Glasgow 0·17, Boston 0·17, Montreal 0·147, Niagara 0·167, Halifax, N. S., 0·159, New York, Cleveland, and Chicago 0·184, Philadelphia 0·194, Washington 0·20, Berlin 0·178, Paris 0·188, Rome 0·24, San Francisco 0·255, New Orleans 0·82, Mexico 0·31, Bombay 0·33.)

Now, the current that is so strong as to fulfil the above definition is far stronger than anything used in telegraphic work, being about as great in quantity as the current in an arc-light circuit. Accordingly *the practical unit* of current is fixed at one-tenth part of the absolute unit, and it is called "one *ampere.*" It follows that the above equation, when i is to be given in amperes, must be altered to

$$i = \frac{10\,r\,H}{2\pi S} \tan \delta.$$

It may further be noted that the current of one ampere strength will cause the deposition in one hour of 1·174 grammes, or 18·116 grains of copper in a copper electrolytic cell. It will in 1 hour deposit 4·024 grammes, or 60·52 grains, of silver in a silver cell. The Committee of the Board of Trade in their Report of 1891, while adopting as the abstract definition of the ampere that given above, also add as a secondary or working definition *that an unvarying current which, when passed through a solution of nitrate of silver in water* (in accordance with the specification attached to their Report), *deposits silver at the rate of* 0·001118 *of a gramme per second, may be taken as a current of one ampere.* They add that an alternating current of one ampere shall mean a current such that the square root of the time average of the square of its strength at each instant in amperes is unity. This is what is called in this book (see p. 631) one "virtual ampere."

The other electrical units also require definition. The *electromotive-force* of a battery, or of a dynamo, is only another name for the power which it possesses to drive electricity through a circuit. (Formerly the electromotive-force of a battery was called its "intensity" as a distinction from the "quantity" of current it would furnish.) It is also sometimes called the electric "pressure." As a basis for a unit of electromotive-force any one of the following experimental facts might have been selected. The electromotive-force is proportional, (1) to the current that it sets up in a circuit of given resistance; (2) to the quantity of electricity that it will force as a charge into a condenser of given capacity; (3) to the number of lines of magnetic force cut per second by a conductor moving in a magnetic field. The first of these would do if the unit of resistance were given, but it is more convenient to make this fact the basis of definition of that unit rather than of the unit of electromotive-force; the second is useful for defining the unit of capacity; the third is selected for defining the unit of electromotive-force, and is extremely appropriate for the purpose, as it is the very principle of the dynamo machine. Clearly, that electromotive-force ought to be reckoned as of unit value which is produced by the motion of a conductor cutting across one line of magnetic force in one second. But this involves the preliminary definition of the unit line of magnetic force. This is as follows:—The so-called magnetic lines of force represent by their direction, the direction of the resultant magnetic force in the space through which they pass: the space traversed by magnetic forces, and lines of force being called a magnetic "field." To make the number of magnetic lines represent *numerically*, as well as in mere direction, the intensity of the magnetic forces, the following device is adopted. Remembering that experiment shows that the pull (or push) which a magnetic pole experiences when placed in a magnetic field is proportional to the intensity of that field, let there be drawn as many lines to the square centimetre as there are dynes of force exerted on the unit pole. For example, if at any point it was found that the magnetic pull on a unit pole was 40 dynes, then at that place we should draw, or imagine to be drawn, 40 magnetic lines all packed within one square centimetre of sectional area. As the earth's horizontal component at London is only 0.18 (dynes on the unit pole) it follows that there would be only 18 lines passing through an area of 100 square centimetres set up vertically east and west. Returning to the definition of electromotive-force, we see that if the moving conductor cuts one magnetic line in one second) the electromotive-force generated will be of unit value in this absolute C.G.S. system of measurement. But such a unit would be ridiculously small—far too small for practical use. Measured in such units the electromotive-force of a single Daniell's cell would be represented by the enormous number of 110,000,000, and a Latimer-Clark standard cell by 143,500,000 units. Hence practical electricians adopt, as their working unit, an electromotive-force one hundred million times as great as the absolute C.G.S. unit; and they call the practical unit "one *volt*." Hence the definition of "one volt" is that electromotive-force which would be generated by a conductor cutting across a hundred million (10^8) magnetic lines per second. The electromotive-force of a Daniell's cell is about 1·1 volts; that of Clark's standard cell 1·435 volts. The Board of Trade accepts this figure as being within 1 per cent. of the true value. The appropriate instruments for measuring volts is called a *volt-meter*. For alternating electromotive-forces, the unit legally recognized by the Board of Trade is that called in this book (see p. 631) "virtual volts."

We come then to the unit of electrical *resistance*. It is found by experiment that the current which is produced in a circuit by applying a given steady electromotive-force depends on the resistance offered by the circuit to the flow of electricity, the current being less as the resistance is greater, in accordance with the famous law discovered by Dr. Ohm.

Ohm's law, in fact, states that the current is directly proportional to the electromotive-force that is exerted in, and is inversely proportional to the resistance of, the circuit. If the symbol E stands for the number of units of electromotive-force, and R for the number of units of resistance of the circuit, and i for the current that results, then Ohm's law will be written :—

$$\frac{E}{R} = i,$$

or, the resulting current can be calculated by dividing the number of units of electromotive-force by the number of units of resistance. Another way of writing Ohm's law, which is useful when it is desired to calculate the electromotive-force that will drive any prescribed current through a given resistance, is

$$E = Ri.$$

Now suppose we had an electromotive-force equal to one absolute C.G.S. unit, and we require to produce by its means a current of unit strength as previously defined in the absolute system, it would be requisite to adjust the resistance of the circuit to a definite value ; and that value would be extremely small, otherwise such a minute electromotive-force could not maintain so large a current. Nevertheless this very minute resistance would be rightly taken as the unit in the absolute C.G.S. system, for then Ohm's law would be numerically fulfilled as

$$\frac{\text{one unit of electromotive-force}}{\text{one unit of resistance}} = \text{one unit of current.}$$

But as there are already practical units of electromotive-force and of current, so there is required a practical unit of resistance to correspond. And reflection will show that the practical unit must be a thousand million times as great as the absolute unit. For then, again, Ohm's law will be fulfilled as

$$\frac{\text{one hundred million C.G.S. units of electromotive-force}}{\text{one thousand million C.G.S. units of resistance}}$$

$$= \text{one-tenth C.G.S. unit of current.}$$

The name of one "*ohm*" is given to this practical unit of resistance ; and many researches have been made to determine its working value. The British Association Committee produced standard wire coils, which were long accepted as being exact *ohms*, but they are now known to be all slightly too low in resistance. In 1882 the International Congress fixed upon *the value of the ohm* as being *a resistance equal to that of a column of mercury one square millimetre in cross-section, and* 106 *centimetres long* (measured at the freezing-point of water). According to Lord Rayleigh's most careful measurements, the true ohm ought to be, not 106, but 106·3 centimetres long. The Report of the Committee of the Board of Trade adopts this more exact value and makes it the legal definition of the ohm in Great Britain.

The resistances of wires and circuits are measured in practice by comparing them with certain standard "resistance coils," sets of which are often employed arranged in "resistance boxes" ; the particular instruments employed in making the comparison being of two kinds, namely, the differential galvanometers and the Wheatstone's bridge. For further information the reader must refer to the text-books on electric testing.

A rough and ready idea of the resistance called "one ohm" may be obtained by remembering that a mile of ordinary iron telegraph line offers from 13½ to 20 ohms resistance.

Another unit is required by electricians, namely, a unit of *power*, in which to express the quantity of work per second done in any electrical resistance.

To measure the rate at which work is done by a current in a wire, or in a lamp, or other thing supplied with electric power, we must measure both the *amperes* of current that are running through it, and the *volts* of electromotive-force that are actually applied at that part of the circuit, and having found the two numbers we must multiply them together. For just as engineers express power mechanically as the number of "foot-pounds" expended in a given time, so the electrician expresses electric power as the number of "volt-amperes." The more convenient name of "one *watt*" is given to the unit of electric power. Calculation shows that one "watt" or "volt-ampere" is equal to one seven-hundred-and-forty-sixth part of a horse-power.

As an example of calculation of electric power the following may be taken. It was required to ascertain the power expended in maintaining a certain arc lamp. The voltmeter showed an electric pressure of 57 volts between the terminals of the lamp, and the amperemeter showed a current of 10·5 amperes running through it. The product is 598·5 watts. Dividing by 746 to bring to horse-power, we get 0·80, or eight-tenths of a horse-power. The name *kilowatt* is given to 1000 watts. One kilowatt is slightly more than 1⅓ horse-power. As a unit of electric energy, the legal quantity recognized by the Board of Trade for the purposes of public supply, is that amount of energy supplied in an hour by a circuit delivering power at the rate of 1000 watts; or, briefly, the *Board of Trade unit* is *one kilowatt hour*.

The unit of self-induction, called by various names, *secohm*, *quad* or *quadrant*, and *henry*, is a derived unit of modern origin. Whenever a current is varying in strength, it will, if carried round a coil, set up magnetic lines which as they alter in number act inductively on the convolutions of the conductor, and set up induced electromotive-forces which tend to oppose the change in value of the current. The symbol used for a coefficient of self-induction is usually L: and bears the meaning that if unit current were suddenly turned off or on in the circuit in question, the resulting amount of cutting of magnetic lines by the convolutions of the circuit would have the value L. The practical unit, to correspond with volt, ohm, &c., is taken as 10^9 C.G.S. units, or one ohm second; or a coil will be said to have as the value of its coefficient one *henry* (or *quadrant*, or *secohm*) if, when unit current is turned on in it, the cutting of its own magnetic lines which results is as much as if 10^9 magnetic lines had been each cut once by a single convolution. If the rate of change of current at any time be expressed as $\frac{di}{dt}$, then the resulting self-induced electromotive-force opposing the change will be :—

$$= - L \frac{di}{dt}.$$

For a given form and volume of coil, the coefficient of self-induction is proportional to the square of the number of convolutions. The presence of an iron core vastly increases the self-inductive effects, but renders the coefficient of self-induction a variable quantity because of the variations in the permeability of the core. The instrument devised by Ayrton and Perry for measuring coefficients of self-induction is called a *secohmmeter*. For further details the reader is referred to treatises on the theory of electricity. He should also consult a valuable article by Mr. Kennelly in *Electrical World*, xvi. 452, 1890.

APPENDIX B.

On Wires.

On p. 422 were given some data respecting the sizes of wire found suitable in practice for winding dynamos for different currents. Other data are to be found in the detailed descriptions of various machines in other parts of this book. Further, on p. 425 were given some formulæ for calculating the weights of wire needed for magnet coils. The question of heating in relation to current-carrying capacity was also treated in Chapter XV. in some detail.

A few further points may be added here founded upon information given by wire-makers, and in particular by the London Electric Wire Company.

The usual insulation for round wires of a greater diameter than No. 16 S.W.G. is a double cotton covering which increases the diameter by amounts varying from 10 to 20 mils, but which usually averages 14 mils. For smaller sizes, from No. 18 to No. 22 S.W.G., the usual double cotton covering is an addition of 12 mils. Square wire is usually double-cotton covered to 20 mils additional, or is sometimes braided. Laminated square wire, *i. e.* made of a number of narrow strips, is usually braided to about an equal amount. Since stranded wires came in for armature winding, several modes of insulating have been adopted, and one maker employs a cable of 37 wires, each No. 15 S.W.G., each single-cotton covered; the whole being double-cotton covered to 16 mils additional, or braided to 20 mils. For transformer windings at high voltage a frequent practice is to wind a much thicker cotton insulation for subsequent immersion in oil. For example, a No. 23 S.W.G. wire is cotton covered to 40 mils additional, thus nearly doubling the weight of the wire.

Annexed is a table useful in magnet winding, showing the probable heating, and greatest permissible depth of winding at various amperages. It is to be remembered that 2000 amperes per sq. in. is a common density of current for field-magnets; whilst armatures run to 3000 or more.

APPENDIX B.—*continued.*

Wire Gauge and Amperage Table.

Dimensions.				Permissible Amperage, Probable Heating, and Permissible Depth.											
S. W. G.	Diam.	Section (sq. inch).	Turns to 1 linear inch.	1000 Amperes to sq. inch.			2000 Amperes to sq. inch.			3000 Amperes to sq. inch.			4000 Amperes to sq. inch.		
				A	F	D	A	F	D	A	F	D	A	F	D
22	·028	·00062	23·81	·616	0·91	4·5	1·23	3·63	1·13	1·85	8·16	·50	2·46	14·5	·28
20	·036	·0010	20·00	1·018	1·29	3·9	2·036	5·17	·97	3·05	11·6	·43	4·07	20·7	·24
19	·040	·0012	18·52	1·26	1·53	[illegible]·6	2·52	6·02	·92	3·78	13·8	·41	5.04	24·5	·23
18	·048	·0018	16·13	1·81	1·83	3·3	3·62	7·32	·88	5·43	16·4	·37	7·24	29·3	·21
17	·056	·0024	14·28	2·4	2·14	3·2	4·8	8·56	·79	7·2	19·3	·35	9·6	34·2	·19
16	·064	·0032	12·83	3·2	2·57	3·0	6·4	10·28	·74	9·6	23·1	·33	12·8	41·1	·18
15	·072	·0040	11·63	4·0	2·90	2·9	8·0	11·6	·72	12·0	26·2	·32	16·0	46·4	·17
14	·080	·0050	10·64	5·0	3·33	2·8	10·0	13·3	·70	15·0	30·0	·31	20·0	53·3	·17
13	·092	·0060	9·44	6·6	4·29	2·7	13·2	17·2	·67	19·8	38·7	·30	26·4	68·8	·16
12	·104	·0085	8·48	8·5	4·52	2·6	17·0	18·1	·65	25·5	40·7	·29	34·0	72·3	·16
11	·116	·0105	7·69	10·5	5·07	2·5	21·0	20·3	·63	31·5	45·7	·28	42·0	81·2	·16
10	·128	·0128	7·04	12·8	5·67	2·4	25·6	22·7	·61	38·4	51·0	·27	51·2	90·7	·15
9	·144	·0163	6·33	16·3	6·50	2·4	32·6	26·8	·60	48·9	58·5	·27	65·2	104·5	·15
8	·160	·0201	5·74	20·1	7·28	2·3	40·2	29·1	·59	60·3	65·5	·26	80·4	116·4	·15
7	·176	·0243	5·26	24·3	8·06	2·3	48·6	32·2	·58	72·9	72·6	·26	97·2	120·0	·15

Strand'd																
$\frac{7}{22}$	·084	·0043	9·62	4·3	2·59	4·0	8·6	10·3	·99	12·9	28·3	·44	17·2	41·4	·25
$\frac{7}{20}$	·108	·0072	7·81	7·13	3·45	3·7	14·3	13·8	·92	21·4	31·2	·48	28·5	55·2	·23
$\frac{7}{18}$	·144	·0128	6·09	12·7	4·94	3·4	25·4	19·7	·83	38·1	44·5	·39	50·8	79·0	·21
$\frac{7}{16}$	·192	·0229	5·10	22·9	7·37	3·2	45·8	29·5	·79	68·7	66·3	·35	91·6	117·9	·20
$\frac{7}{15}$	·216	·0289	4·27	28·9	7·79	3·1	57·8	31·2	·78	86·7	70·1	·34	115·6	124·6	·20
$\frac{7}{14}$	·240	·0356	3·87	35·6	8·72	2·7	71·2	34·8	·76	106·8	78·4	·34	142·4	139·5	·19
$\frac{7}{13}$	·276	·0452	3·38	46·2	9·91	2·0	92·4	39·6	·74	138·6	89·2	·33	184·8	158·5	·19
$\frac{7}{12}$	·312	·0595	3·01	59·5	11·4	1·9	179·0	45·5	·72	178·5	102·5	·32	238·0	182·2	·18

Figures in columns marked **A** signify number of amperes that the wire carries.

Figures in columns marked **F** signify number of degrees (Fahrenheit) that the coil will warm up if there is only one layer of wire; they are calculated by Esson's modification of Forbes' rule:—

Rise in temperature (Fahrenheit degrees) = 100 × number of watts lost per sq. inch.
= 69 × sectional area × number of turns to 1 inch (at 1000 amperes per sq. inch).

Figures in column marked **D.** are the depths in inches to which wire may be wound if 1 watt be lost by each square inch of radiating surface, the outside radiating surface of the bobbin only being considered.

Rule for calculating a 7-strand cable:—Diameter of cable = 1·134 × diameter of equivalent round wire.

Figures under heading "Turns to 1 linear inch" are calculated for cotton covered wires of average thicknesses of coverings used for the different gauges, viz.: 14 mils additional diameter on round wires (from No. 22), and 20 mils on stranded or square wire.

Resistance (ohms) of coil of copper wire, occupying v cubic inches of coil space, and of which the gauge is d mils uncovered, and D mils covered, may be approximately calculated by the rule:—

$$\text{ohms} = 960700 \frac{v}{D^2 d^2}$$

INDEX.

A.

PAGE.

Absolute system of Units (Appendix A.) ... 809
Accumulators, Charging of ... 275, 277
Achard, on Efficiency of Motors ... 560
Act, the, of Commutation ... 85, 222, 587
Activity (*see* Power) ... 109, 559
  " Maximum, of Motor ... 561, 567
Adams, W. Grylls, Tests made at Crystal Palace Exhibition ... 794
  " " Inaugural Address ... 794
  " " On Alternate-current Dynamo ... 696
Admiralty, Rule of Heating ... 429
" Agir " Motor (*see* Anderson)
Air Blast ... 472
Air Gap ... 150, 176, 410, 433, 438
Algebraic Theory ... 207
Alioth's Dynamos ... 331, 372
Allan's Armature ... 44
Allen, W. H. & Co ... 487
Allgemeine Company ... 43, 533, 713
" Alliance " Machine ... 11, 645
Alignment of Bearings ... 393
Alsacian Co.'s Dynamos ... 388, 433
Alteneck, von Hefner ... 16, 361, 664
Alternate-Currents, distribution of ... 721
  " " principles of ... 618
  " " measurement of ... 633
  " " multiphase ... 687
Alternate-Current Dynamos (*see* Alternators)
Alternators, Coupling of ... 689
  " Theory of ... 48, 618, 650
  " Excitation of ... 652
  " Field-magnets for ... 203, 652, 678, 689
  " Theory of Armature Winding ... 313, 640, 648, 650
  " Collecting Arrangments for ... 373, 386, 648, 674, 806
  " Permissible Speed of ... 421, 675, 676
  " Constant-current ... 686
  " High Frequency ... 637
  " Multiphase ... 687
  " Inductor ... 683

PAGE.

Alternator, Mordey's 18, 393, 676
“ “ (Inductor) 683
“ Alliance 11, 645
“ Blakey-Emmott's 386, 661
“ Brown's (Three-Phase) 18, 688
“ Elihu Thomson's 659
“ “ “ (Inductor) 686
“ Elwell-Parker's 667
“ Ferranti's 668
“ Gordon's 667
“ Hopkinsons' 662
“ Kapp's 654
“ Kingdon's (Inductor) 684
“ Kennedy's “ 686
“ Parsons' 676
“ Siemens' 664
“ Stanley's (Westinghouse) 657
“ “ (Constant Current) 686
“ Zipernowsky's (Ganz's) 662
Amperage, permissible in wires 399, 405, 681, 818
Ampère's Rule 22
Ampere, the, Unit of Current 812
Ampere-turns 125, 150, 181, 408, 411, 419, 602, 724
Andersen and Girdlestone, their Motor 384, 612
Angle of Lag 627, 630, 634, 636, 743
“ Lead of Brushes 83, 87, 436, 587
“ Polar Span 79, 403, 437, 650
Angular Velocity 108, 421, 675
Apparent Resistance 95, 629
“ Watts 636, 739
Arc Lighting, Dynamos for 447
“ “ “ Brush's 455
“ “ “ Thomson-Houston 464
“ “ “ Ball's 476
“ “ “ Sperry's 475
“ “ “ Wood's 476
“ “ “ Edison's Municipal 477
“ “ “ Phœnix 477
“ “ “ Statter's 478
“ “ “ Schuyler's 478
“ “ “ Stanley's (Alternator) 686
Arc, Voltaic 273, 274, 447
Armature Coefficient 208
Armatures, Balancing of 354, 391, 805
“ Binding of 43, 113, 349, 355, 659
“ Bar 356, 363, 487, 509, 547

PAGE.

Armatures, Burning-out of.. 803
" Function of.. 2, 35,208
" Driving, Contrivances for...................... 347, 354, 487
" Disconnexions in.. 804
" Classification of............................... 41, 314, 640
" Construction of.............................. 342, 356, 640
" Coils of... 301
" " Method of securing (*see* Binding of)
" Cores of...................... 42, 342, 401, 407, 421, 643, 653
" Diameter of..................... 401, 402, 431, 654, 666, 676
" Disk.............................. 16, 41, 45, 337, 544, 645
" Drum.......................... 41, 303, 318, 326, 361, 643
" Pole.. 41, 644
" Ring............................ 36, 41, 302, 315, 343, 640
" Closed Coil...................................... 39, 314
" Open Coil.................................. 17, 449, 473
" Heating of.......................... 353, 422, 426, 681, 803
" Hole (*see* Perforated)
" Limit of Load of.......................... 435, 439, 654, 681
" Length of.................. 98, 401, 403, 431, 440, 444, 654
" Induction by................................ 36, 73, 474, 619
" Induction, Magnetic, in.................... 401, 422, 651, 656
" Insulation of..................... 45, 353, 355, 455, 655, 672
" Perforated................................... 346, 490, 688
" Radial Depth of................................... 401, 421
" Section of.. 40, 400
" Reactions due to.......................... 74, 436, 544, 585, 653
" Spiders.. 347
" Ventilation of................... 203, 347, 349, 353, 489, 681
" Winding of.......................... 301, 358, 399, 422, 487
" Shuttle-wound........................... 12, 33, 359, 361, 552
" Lamination of................................ 45, 96, 342, 461
" Misused to Magnetize Field-Magnets................. 92, 588
" with several Independent Circuits.............. 315, 509, 539
" Formulæ for winding.................................... 315
" Arnold's.. 529
" Alioth's... 331, 372
" Bollmann's...................................... 339, 546
" Brown's.. 346
" Brush's.. 17, 462
" Bürgin's.. 345
" Crompton's.. 349
" Desroziers'... 339
" Edison's.. 364
" Eickemeyer's.. 371
" Ferranti's.. 669, 672

PAGE.

Armatures, Fritsche's 44
" Gramme's 344
" Hookham's 839
" Kapp's 488
" Hopkinson's 366
" Lontin's 16
" Mordey's Multipolar 335
" " Alternate 679
" Pacinotti's 14, 16, 346, 545
" Perry's Multipolar 337
" Schuckert's 523
" Siemens's 318
" Stanley's 637
" Sturgeon's 33
" Swinburne's (*see* Crompton's).
" Thomson-Houston's 466
" Wallace-Farmer's 545
" Wilde's 645
" Wodica's 317

Arnold, on Theory of Winding 21, 302 315, 337

Arnoux, R., on Theory of Winding 302, 339
" on Effect of Gap Space 434
" on Load Curves 435

Ascending Curves of Magnetism 142, 182

Atkinson, Ll. B. (*see* also Goolden).
" Unipolar Dynamo 544
" Alternate-current Motors 702
" Mining Motor 615
" Mining Drill 617

Auerbach (*see* Myer).

Automatic Regulator (*see* Governors).

Auxiliary Reversing Pole 93, 441

Average Electromotive-force 211, 631

Ayrton, W. E., on Demagnetizing Effect of Armature 92, 588
" on Capacity and Size 119
" Three-voltmeter Method 633
" and Perry Commutator 375
" " Dynamo 545
" " Dynamometer 787
" " Magnetic Shunts 186
" " Motor 592, 609
" " Theory of Governing Motors 595, 597, 602
" " on Measurement of Discontinuity 222
" " on Apparent Resistance of Armature 95
" " on Proper Thickness of Winding 455
" " on Curves of Torque 115
" " on Transmission of Power 560

B.

PAGE.

BABBITT Metal, for Bearings 393
Back Electromotive-force (*see* Counter Electromotive-force)
  " Induction 89
Baker, on Self-excitation 13
Baking Armatures in Stove 358, 378
Balancing of Armature 354, 391, 805
Ball-bearings 394
Ball's Arc-light Dynamos 476
Bar Armatures 356, 363, 487, 509, 547
Barley and Stevenson's Brush-holder 385
Barlow's Wheel 18
Bars of Commutator (*see* Commutator)
Baumgardt, M., on Compound Winding 300
Bearings, Proper Design of 392
  " Thrust 393, 680
  " Pressure on 387
  " Lubrication of 394, 675, 682
Bed-plates 36, 183, 196, 396, 800
Bell, Louis, on compound Winding 300
Belts for Driving 396, 800
Bending Moment of Shafts 391, 805
Berlin Central Station Dynamos 512
Bertin, on Shunt-winding 16
Bidwell, S., on Magnetization of Iron 137, 147
Bifurcation of Current 301
Binding wires of Armature 43, 113, 349, 355, 659
  " " proper size of 355
Blakesley, T. H., on Phase of Alternations 628
  " " Three-dynamometer Method 633
Blakey, Emmott & Co.'s Dynamos 201
  " " Alternators 386, 661
Board of Trade Unit 816
Bobbin (*see* Armature).
Bollman's Armature 339, 546
Bosanquet, R. H. M., on Magnetization of Iron 134, 135, 146, 167, 172
Bourbouze's Motor 550
Brackett, Cyrus F. (his Dynamometer) 232, 789
Bradley, on Multipolar Winding 333
  " Multiphase Motor 714
Branched Magnetic Circuits 205
Break-down, causes of 377, 802
Breguet, Antoine 4
Brett, Jacob, his self-exciting machine 10, 12
Brotherhood's Coupling 397
Brown, C. E. L., his Dynamos 197, 396, 490, 540, 544, 759, 766

PAGE.
Brown, C. E. L., Pierced Core-disks 347, 490, 688
“ Multiphase Alternator 688
“ “ Motor 713
“ Transformer 738
“ Field-Magnets 200, 204, 689
“ Mode of Driving Core-disks 351
“ Sliding Contact Device 386, 689
“ Design of Shaft 392
Brush's Armature 454
“ Automatic Regulator 772
“ Commutator 457
“ Induction-sheath 454
“ Motor 595
“ Compound-winding 59
“ Dynamo 17, 454, 457
“ “ Characteristic of 256
“ “ Teazer Circuit of 59, 538
Brushes, the 2, 32, 35, 41, 379
“ Automatic Adjustment 470, 478, 768
“ Difference of Potential at 70, 226, 228
“ Lead of 83, 86, 87, 436, 587
“ Proper Width and Thickness of 87, 380, 539
“ Rotating 380
“ Carbon 380, 382, 532
Brush-holders 382
Bürgin (*see* Crompton).

C.

CABANELLAS, G., on Motor-generators 720
“ “ on Apparent Resistance of Armatures 95
Cabella's Dynamo 200
Calculations in Designing 404, 438, 608, 650, 759
Capacity of Machines 117, 438, 608, 654
Carbon Brushes 380, 382, 532, 661
“ Plates in Rheostat 773
Cardew's Voltmeter 631
“ Researches on Phase 731
“ Method of Testing 790
Carhart on Magnetic Leakage 184
Cast Iron (*see* Iron).
Causes of Sparking 83, 436, 441
Central Station Dynamos 201, 370, 487, 489, 509, 510, 516, 520, 523, 525, 530, 657, 666, 668, 674, 681, 686
Centrifugal Force on Armatures 113, 119, 355
“ Governors of Motors 501, 594
Chamberlain and Hookham's Dynamos 346

PAGE.
Characteristic Curves of Dynamos 230, 245, 266, 296, 299, 433
“ “ External 256
“ “ Internal 261
“ “ Discovery of 246
“ “ Method of taking 247
“ “ Predetermination of 175, 181
“ “ Drooping of 256, 479
“ “ and Horse-power Lines 249
“ “ Mechanical, of Motors 574, 577, 604
Charging Accumulators 275, 277
Chwolson's Researches 167
Circuit, Electric 27
“ Magnetic 171, 409
“ Open 450
“ Teazer 59
Circumflux (or Circulation per Pole) 437, 438
Clark's Dynamo 197
Clark, Muirhead & Co 197, 534
Clarke's Magneto Machine 5
Classification of Machines 1, 41, 49
“ of Armatures 41, 311, 356, 639
“ of Motors 576, 598, 605, 640
“ of Alternate-current Motors 700, 710
Clausius, R., on Theory of Dynamo 20, 101, 237
Clearance 404, 443, 445, 475, 490
Clerk-Maxwell (*see* Maxwell).
Closed-coil Armatures 39, 314, 707
Coercive Force 159
Collector (*see* Commutator),
“ of Alternator 35, 373, 386, 648, 674, 806
Combination Methods of Winding Magnets 56, 280, 598, 659, 747
Commutation, the Act of 85, 222, 587
“ Diameter of 33, 44, 76, 83, 324, 587
Commutator, Function of 2, 30, 32, 35, 41, 64, 374, 587
“ Insulation of 375, 807
“ Potential at 68, 460
“ Construction of 373
“ External 512, 547
“ Proper size of 379
“ Flats in 805
“ Brush's 457
“ Crompton's 374
“ Hochhausen's 375
“ Paterson and Cooper's 375
“ Holmes's 527
“ Hopkinson's 521

PAGE.
Commutator, Gülcher's.. 376
" Kapp's 376
" Siemens's.. 508
" Edison-Hopkinson's.. 521
" Immisch's.. 611
" Mountain's 529
" for Alternators.. 373, 652
" Deterioration of.. 802, 805
" Elihu Thomson's.. 467
" Ventilation of.. 375, 472
Compensating Coils.............................. 280, 285, 436, 598, 659, 747
" Poles.. 93, 441
Composite Excitation.. 56, 659
Compound Winding.............................. 13, 18, 60, 280, 597
" " Best Method of.. 294
" " Theory of.. 289
" " Brush's.. 454
" " Crompton's.. 280
" " of Motors.. 590, 597, 603
" " Esson on.. 299
" " Frölich on.. 292
" " Gülcher's.. 299
" " Siemens's.. 293, 508, 509
" " Watson's.. 605
" " E. Thomson's.. 294, 473, 659
" " Slow-acting 295
Compression, Effects of, on Magnetism.. 156, 353
Connectors of Armature.. 363, 369, 378
Connexions, Theory of.. 301, 363
" Faults in.. 804
Consequent Poles.. 198
Constant-current Distribution..............................56, 277, 448, 574, 753
" " Dynamos.. 447
" " Alternators.. 686
" " Regulators.. 769
" " Motors.. 607, 616
" " Transformers.. 747
Constant-potential Distribution.. 56, 574, 753
" " Dynamos.. 277
Construction, Principles of.. 342
Contact, Line of, on Commutator.. 83, 801
Contact-Rings of Alternators.............................. 373, 386, 648, 674, 806
Continuity of Currents.. 38, 214
Continuous-current Machines.. 35, 36
" " Transformers.. 748
Conversion, Efficiency of.. 116, 791

PAGE.
Converters (*see* Transformers).
Cooke (*see* Wheatstone).
Cooling-surface 425, 429, 443
Copper, Deposition of 540
“ Quality and Quantity of 422, 436
“ in Armature, Weight of 425
“ Heat lost in 423
Cores 45, 97, 342, 401, 407, 461, 644, 734
“ Lamination of 45, 96, 342, 461, 734
“ Eddy-currents in 97, 461
Core-disks, diameters of 401, 421
“ Choice of 401
“ Radial Depth of 401, 421
“ Toothed 346, 493, 528
“ Perforated 347, 490, 688, 714
“ Segmental 343, 666, 667
“ Thickness of 98, 342, 421, 654
“ Modes of Driving 347, 351, 528
“ Insulation of 45, 343, 487, 518, 610, 654
“ Ventilation of 347, 353, 489
Cost of Field-magnetism 52, 415, 425, 682, 689
Counter Electromotive-forces in Armature of Dynamo 87, 768
“ “ “ of Motor 553, 554, 701
“ “ “ of Self-induction 622, 628, 729, 817
“ “ “ in Voltaic Arc 447
Couple (*see* Torque).
Coupling of Dynamos 689, 795
Couplings for Direct-driving 397
Creeping of Magnetism 88, 165
Critical Current 260
“ Speed 58, 60, 261, 282, 544, 600, 784
Crompton, R. E., his Armature 17, 349, 355, 369, 485
“ “ on Compound-winding 61
“ “ on Stranding of Conductors 357, 487
“ “ Winding of Armatures 360, 369, 485
“ “ uses Alloy for Commutator 375
Crompton-Bürgin Dynamo 345, 485
“ Dynamo, Field-magnets of 197
Crompton-Kapp (*see* Crompton).
Crompton-Kyle Winding 369
Crompton-Swinburne Drum Armature 367, 487
Cross-connecting of Armature-windings 317, 333, 500, 502, 540, 585
Cross-induction (*see* Cross-magnetizing Effect).
Cross-magnetizing Effect of Armatures 74, 78, 91, 401, 437
“ “ “ Expedients against 79, 206, 434, 441, 528
Current, Constant, Distribution with 56, 277, 448, 574, 753

PAGE.

Current, Constant, Arrangements for.................. 448, 574, 753, 769
" " Motors supplied with.......................... 605
" " Economy of.......................... 755
" Critical, of Machine.......................... 261
" Diacritical, of Field-magnet.......................... 166
" Alternations of.......................... 618
" Continuity of.......................... 38, 214
" Equations of, in Series Machines.......................... 237
" " in Shunt " 238
" Rectified or Redressed.......................... 38, 452
" Unit of (the *ampere*).......................... 812
" Density.......................... 399, 422, 681, 764, 818
Currents, Eddy.............. 74, 95, 346, 353, 366, 461, 487, 498, 608, 702, 704, 707, 727, 745
" Foucault's (*see* Eddy).
" Parasitical (*see* Eddy).
Curves of Magnetization.......................... 132, 140
" of Torque.......................... 114
" of Potential at Collector.......................... 67, 70, 72, 256
" Characteristic......................230, 245, 266, 296, 299, 433, 577
Cutting of Magnetic Lines......................22, 26, 207, 542, 619, 722
Cuttriss's Motor.......................... 616
Cycles of Magnetization.......................... 160, 730
" of Alternation.......................... 619, 639

D.

Dal Negro's Magneto Machine.......................... 8
" " Motor.......................... 18, 550
Davenport's Motor.......................... 18
Davidson's Motor.......................... 18, 552
Davis, on Principle of Reversibility.......................... 19
Dead Points in Motors.......................... 705
" Turns.......................... 96, 226, 257
Definition of Dynamo-machine.......................... 1
Demagnetizing Action of Armature, 89, 91, 92, 255, 285, 412, 416, 436, 585
" " of Eddy Currents.......................... 89, 225, 588
" " of Secondary Current.......................... 724
" " Expedients against.......................... 93, 412, 416
De Meritens's Alternator.......................... 642
Density, Permissible, of Current in Coil...... 399, 405, 425, 681, 746, 818
" " of Magnetic Lines in Core... 401, 402, 422, 651, 730
Deprez, Marcel, Brake.......................... 786
" " Characteristic Curves.......................... 20, 247, 254
" " Dynamo.......................... 198
" " Experiments of Transmission of Power.......... 19, 756
" " on Field-magnets.......................... 198, 231
" ' Law of Similars.......................... 118

PAGE.
Deprez, Marcel, on Self-Regulating Combinations......... 18, 56, 58, 296
" " Motors.................................. 594, 617
" " Transmission by Transformers.................... 720
" " on Cost of the Torque............................ 115
Depth, Radial, of Core....................................... 401, 421
" Maximum Permissible of Winding.......................... 819
Derivation (*see* Shunt).
Descending Curves of Magnetization.......................... 142
Design of Dynamos............................ 46, 243, 295, 398, 441
" of Alternators.. 650, 654
" of Motors.. 608
" of Transformers.. 730
Desroziers's Disk Dynamo........................... 45, 339, 546
Developed Winding Diagrams................................. 307, 687
Diacritical Point (*see* Saturation).
Diamagnetic Substances....................................... 130
Diameter of Commutation........................ 33, 44, 76, 83, 324, 587
Difference of Potential.. 68, 228
" " Constant.............................. 229, 277
" " " Combinations for................. 280
Dip of Characteristic.. 255, 479
Discharge of Magnetism.................................. 259, 263, 265
Discoidal Ring Armatures........................... 42, 343, 355, 421
Discontinuity of Currents........................... 38, 214, 222, 474
" Magnetic.................................. 152, 195, 343
Diseases of Dynamos............................ 88, 375, 379, 474, 802
Disk Armatures............................ 16, 41, 45, 337, 421, 544, 645
Disk Dynamo, Edison's.................................. 17, 339, 340, 545
" " Faraday's.. 6, 542
" " Pacinotti's.................................. 16, 337, 545
" " Fritsche's.................................... 44, 339, 547
" " Desroziers'.................................. 45, 339, 546
Distortion of Magnetic Field.............. 72, 73, 76, 79, 81, 94, 103, 586
Dobrowolsky, von Dolivo, on Rotatory-field Motor........... 19, 707, 710
Double Magnetic Circuit, Advantages of......................... 195, 441
" " " Calculation of................................ 206
Drag on Wires carrying Current............ 3, 106, 127, 355, 554, 638, 704
Dreh-strom... 19, 687, 710
Driving, Proper Means for............... 36, 46, 347, 367, 487, 489, 611
Driving-horns.......................... 113, 355, 487, 486, 611, 655
Drooping Characteristic... 256, 479
Drop-forgings Used for Commutator................................. 374
Drum Armatures......... .16, 41, 43, 303, 318, 326, 358, 360, 488, 506, 643
Drying Armature... 358, 378
Du Bois, H. G., his Traction Balance............................. 139
Du Moncel, Count.. 11
Dujardin's Machine.. 11, 17

PAGE

Dynamo, Name of 12
" Definition of 1
" Classification of 1
" Organs of 2
" Alternate-current (*see* Alternators).
" Open-coil 449
" Electroplating 9, 357, 362, 463, 536
" Non-polar 543
" Unipolar 542
" Multiphase 687
" Inductor 683
" Function of in Arc Lighting 447
" Arc Lighting 447
" Diseases of 802
" Far-leading 750
" Equalizing 750
" Management of 800

DYNAMOS of various Inventors:—

Alioth 331, 372
Allan 44
Allen (*see* Kapp).
"Alliance" (Alternator) 11, 645
Allgemeine Co. ("A. E. G.") 43, 533, 713
Alsacian Co 388, 433
Alteneck (*see* Siemens).
Atkinson 544
Ayrton and Perry 545

Bain 479
Ball (Uni-pole-piece, Arc) 476
Blakey, Emmott and Co 210
" " " (Alternator) 386, 661
Bollmann 546
Bradley 333
Brown 396, 490
" (Unipolar) 544
" (Electrometallurgy) 491, 540
" (Three-phase) 688
Brush 454, 538
Brush Co. (*see* Mordey).
Bürgin 101, 305

Cabella 200
Chamberlain and Hookham 346
Clark 197
Clark, Muirhead and Co 535
Clarke 9
Cooper (*see* Paterson).

Dynamos of various Inventors—*continued.* PAGE.
Crompton.................................... 349, 355, 369, 485, 539
Crompton-Bürgin.................................... 305, 485
Crompton-Kapp.................................... 487
Crompton-Kyle.................................... 369
Crompton-Swinburne.................................... 367

Dal Negro.................................... 8
De Meritens (Alternator).................................... 642
Delafield (Unipolar).................................... 543
Deprez, Marcel.................................... 198, 482
Desroziers.................................... 45, 339, 546
Dobrowolsky (*see* Allgemeine Co).
Dujardin (Alternator Inductor).................................... 11, 17

Edison (Tuning Fork).................................... 17, 513
" (Marine).................................... 205
" (Multipolar Ring).................................... 516
" (Drum Armature).................................... 364, 513
" (Disk Dynamo).................................... 339
" (Municipal Dynamo)....................................477
Edison-Hopkinson.................................... 423, 518
Eickemeyer.................................... 203, 371
Elmore.................................... 537
Elphinstone-Vincent.................................... 17, 172
Elwell-Parker.................................... 532, 538
" " (Alternator).................................... 667
Ettingshausen, von.................................... 9
Esson (*see* Paterson)

Faraday.................................... 1, 6, 542
Farmer (*see* Wallace-Farmer).
Fein.................................... 201, 510
Ferranti (Alternator).................................... 668
Ferraris, E. (Unipolar).................................... 543
Firth.................................... 769
Forbes.................................... 200, 543
Foster and Anderson (*see* Clark, Muirhead and Co.).
Fritsche.................................... 322, 547
Fuller-Gramme.................................... 43, 482

Ganz (*see* Zipernowsky).
General Electric Traction Co. (*see* Immisch).
Goolden and Co.................................... 357, 393, 525
Gordon (Alternator).................................... 667
Gramme.................................... 15, 343, 481, 537
" (Alternator).................................... 640
Greenwood and Batley.................................... 530
Gülcher Co.................................... 502

Hammerl.................................... 479
Hefner-Alteneck, von.................................... 16, 361, 545, 664
Heisler (Arc Alternator).................................... 686

Dynamos of various Inventors—*continued.* PAGE.
Henley 11
Hjorth 12
Hochhausen 198, 375, 482
Holmes, F 11, 380, 645, 652
Holmes, J. H., and Co 352, 527
Hopkinson (*see* Edison-Hopkinson).
Hopkinson, J. and E 495, 538
" " (Alternator) 662
Hopkinson and Muirhead 545
Houston (*see* Thomson-Houston).

Immisch 202, 532
"Iron-clad" 200, 506

Jacobi 9
Jehl and Rupp 45, 546
Joel 197, 343
Johnson and Phillips (*see* Kapp).
Jürgensen 198

Kapp 200, 384, 487
" (Alternator) 654
Kennedy 200, 202, 506, 530
" (Alternator) 642, 645, 686
Kingdon (Inductor) 684

Ladd 14, 54
Lahmeyer 185, 200, 529
Laurence, Paris and Scott 326, 528
"Leeds" (*see* Greenwood).
Lontin 16, 200, 644
Lorenz (*see* Jürgensen).

McTighe 202, 495
Main (Alternator) 682
Malderen, van 11
"Manchester" (*see* J. and E. Hopkinson).
Mather and Hopkinson 201, 495
Mordey 497
" (Alternator) 642, 676
" (Inductor) 683
Muirhead (*see* Clark).
Muirhead and Hopkinson (*see* Hopkinson).
Muller 769
Mountain (*see* Ernest Scott and Co.).

Newton 479, 532
Niaudet 101, 545
Nollet 11, 645

Pacinotti 14, 346
" (Disk) 338, 545

Dynamos of various Inventors—*continued.* PAGE.

Page 11
Paris and Scott (*see* Laurence).
Parsons (Alternator) 676
Paterson and Cooper 348, 492, 538
" " (Arc) 477
" " (Alternator) 662
Perry (*see* Ayrton and Perry).
"Phœnix" (*see* Paterson and Cooper).
Pixii 8
Plücker (Unipolar) 542
Polechko (Wheel) 547

Raffard-Gramme 352, 482
Ravenshaw (*see* Goolden).
Ritchie 8
Robin 546
Ruhmkorff 54
Rupp (*see* Jehl).

Sautter-Lemonnier 482
Sawyer 11, 200
Saxton 9, 544
Sayers 546
" (Electroplating) 539
Schorch 202
Schuckert 523
Schuckert-Mordey 204, 497
Schuyler (Arc) 478
Scott (*see* Paris).
Scott, Ernest, and Co 528, 537, 642
Siemens (shuttle) 33
" (drum) 361, 506
" (alternator) 664
" (ring) 510
Sinsteden 61
Snell (*see* Immisch).
Sperry (Arc) 475
Stafford and Eaves (Electroplating) 538
Stanley (Alternators) 643, 657, 686
Statter (Arc) 202, 478
Stöhrer 544
Sturgeon 33
Swan 61
Swinburne 304, 347

"Taunton" (*see* Newton).
Tesla (Alternators) 637
Thomson, Elihu (*see* Thomson-Houston).
Thomson-Houston 534

Dynamos of various Inventors—*continued.* PAGE.
  Thomson-Houston (Arc) 464
    " " (Incandescent) 473
    " " (Alternator) 659
    " " (Inductor) 686
  Thomson, Sir William (Wheel-dynamo) 479, 545
    " " (Alternator) 17, 649, 668
  Thury 201, 331, 535
  Trotter (*see* Goolden).
  "Tyne" (*see* Scott, E., and Co.).

  Van de Poele 198
  Van Malderen (Alternator) 11
  Varley, O. and F 13, 54
  Varley, S. Alfred 13, 61, 542
  "Victoria" (*see* Schuckert-Mordey).
  Vincent (*see* Elphinstone).
  Voice (Unipolar) 543

  Wallace-Farmer 101, 545
  Waterhouse 774
  Watkins 8
  Wenström 200, 347, 535
  Westinghouse (*see* Stanley).
  Weston 348, 355, 537
  Wheatstone 9, 11, 13
  Wilde 11, 50, 54, 201, 203, 537, 646
  Winkler 55
  Wodica 317
  Wood's (Arc-light) 476
  Woolrich 9, 536

  Zipernowsky (Alternator) 201, 644, 662

Dynamometer 785, 787
Dynamometric Governing 595
Dyne (unit of force) 810

E.

EBONITE (*see* Insulating Materials).
Economic Coefficient 117, 232
Economy of Transmission 758, 764
  " Law of Maximum 559, 568, 764
Eddy Currents 74, 89, 95, 346, 357, 366, 461, 487, 498, 608, 681, 696, 702, 704, 707, 727, 739, 745
  " " Demagnetizing Action of 89, 225, 588
  " " Heating due to 357, 461, 644, 727
Edison's Dynamos 17, 513
  " " Armature of 43, 319, 364

PAGE.
Edison's Dynamos, Brushes of 380, 384
" " Field-magnets of 195, 197, 518
" Municipal Dynamo 477
Edison's Disk Dynamo 339, 545
" Tuning-fork Dynamo 17, 518
" Claim for Compound-winding 61
" Regulator 279
Edison General Co.'s Marine Dynamo 205
" " " Multipolar Dynamo 517
" Hopkinson Dynamo 413, 423, 518
" " " Design of 182, 413
" " " Tests on 244
" " " Leakage of 184
" " " Calculation of 189, 412
Efficiency of Dynamo, gross and nett 116, 232, 243, 406, 681
" " Transmission of Power 758, 764
" " " " Maximum 559, 764
" " Motors 556
" " Transformers 739
" " Motor-dynamos 749
" " reduced by Eddy-currents 116, 357, 681
" " Calculations of 117, 405, 415, 526, 529, 758, 764
Eickemeyer, R., Dynamo 201, 202, 203, 371
Electromagnetic Engines (*see* Motors).
" Rules 124, 409
Electromagnets, Formulæ for 165
" First used 7, 10
" Construction of 195, 205, 454
" Cores of 403
" Forms of 195
" Rules for Winding 410, 423
" Internal 510
" Heating of 157, 423
" Ventilation of 507
" Curve of Saturation of 151
" Polarity of 123
Electro-metallurgy 463, 536, 543
Electromotive-force of Dynamo 22, 210
" " and Difference of Potential 68, 229, 277
" " Average 210, 631
" " Fluctuations of 218
" " Unit of (one *volt*) 814
Electromotors (*see* Motors).
Electro-plating, Dynamos for 9, 357, 362, 363, 463, 536
" " Machines unfit for 51, 537
Elementary Theory 207, 618
Elmore's Dynamos 537

PAGE.

Elphinstone, Lord, and Vincent, C. W. 17, 172
Elwell-Parker's Dynamos 197, 201, 532
" " Alternators 667
" " Motor-dynamos 749
Emission of Heat from Surface 426
End-play, when desirable 391
" " " undesirable 391, 393, 680
Energy, Electric 1
" Expended 104, 558, 566
" Utilized 558, 566
" Transmission of 753
Engines, Kerchove's 510
" Kuhn's 512
" Willan's 525, 668
" Ferranti's 676
" Parsons's (Steam Turbine) 676
Equalizing Dynamo 750
Equations of Dynamo 47, 210
" " Frölich's 237
" " Rücker's 237
" of Electromagnets 165
" of Motors 561, 575
Esson, W. B. (*see* also Paterson and Cooper).
" " on Capacity of Dynamos 120, 654
" " on Dynamos at Frankfort 512
" " on Multipolar Dynamos 442
" " on Design of Dynamos 21, 76, 427, 436, 654
" " on Separately-excited Machines 231, 653
" " on Self-regulating Machines 299
" " on Binding Wires 355
" " on Arc-lighting Dynamos 477
" " on Peripheral Speed 421
" " on Wires for Winding 422
" " on Permissible Heating 427
" " on Cooling Surface needed 429
" " on Load Curves 435
" " on Armature Interference 436, 653
Ettingshausen's Machine 9
Evershed, Sydney, on Transformers 738
Ewing, James A., Magnetic Researches 132, 135, 148, 150, 156, 161
" " " on Hysteresis 160
" " " on Effect of Joints 153
" " " on Effect of Compression 155, 156
" " " on Magnetic Creeping 88, 165
" " " Theory of Magnetism 168
Excitation, the (*see* Ampere-turns).
" of Field-magnets, Methods of 49

PAGE.
Excitation, Electromagnet, Law of 165, 177
Exciter, Separate, use of Machine as 50, 231, 659, 662, 680, 689
External Characteristic 253, 261
Extra-current 84

F.

FAILURE of Magnetism 259, 263, 265
Fan, for Ventilation 354
Far-leading Dynamo 750
Faraday's Invention of the Dynamo ......
“ Principle of Induction 2, 22
“ Disk Machine 6, 542
“ Rotating Magnet 8
“ Discovery of Electromagnetic Rotation 18
“ Notion of Magnetic Lines 27, 171
“ Transformer 719
Farmer, Moses G., on Self-excitation 13
Favre, on Theory of Motors 20
Feathers (*see* Keys).
Fein's Dynamos 201
Ferranti's Alternator 17, 203, 647, 649, 668
“ Transformer 721, 737
Ferraris, E., Unipolar Dynamo 543
Ferraris, Galileo, on Efficiency of Transformers 740
“ “ Rotatory Field Motors 19, 703
Field, Distortion of 79, 94, 436, 586
Field, Magnetic 24, 105, 122
“ “ Measurement of 222
“ “ Waste of 98, 180, 182
“ “ Drag of 3, 106, 355, 554
“ “ Rotatory 703
Field-magnets, Construction of 195, 454
“ “ Design of 205, 402, 407, 421, 430, 431, 432
“ “ Coils for 425, 664
“ “ Forms of 195, 431, 432
“ “ Formulæ for 165, 177, 409
“ “ Function of 2, 35
“ “ Heating of 157, 423, 427
“ “ Joints in 152, 195
“ “ Methods of Excitation 49, 280, 602, 604, 659, 747
“ “ Proper Resistance of 237, 243
“ “ Winding of 294, 410, 425, 430, 435
“ “ Advantage of Powerful 48, 87, 103, 561, 576, 588, 592, 608, 616
“ “ Most Powerful in Motors 491, 588, 616, 755, 759, 766
“ “ for Arc-lighting Dynamos 478
Field Rotatory 703

PAGE.
Figures, Magnetic.. 24, 25, 26, 107
Finzi, on Hysteresis.. 164
Flashing-over at Commutator.. 88, 474, 807
Flat-ring Armatures.. 42, 342, 497, 523, 642
" " Advantages of.. 501
Flats in the Commutator.. 805
Fleming, J. A., his Rule for Induction.. 22, 104
" " on Magnetic Reluctivity.. 169
" " on Alternate-current Transformers.. 739
Fluctuations of Current.. 38, 213, 222, 474, 618
" " Measurement of.. 222
Flux, Magnetic.. 47, 176, 400, 406
Fontaine, H.. 19, 757
Foot-steps of Zinc.. 184, 415, 515
Forbes, Georges, his Dynamos.. 200, 543
" " on Waste Magnetic Field.. 175, 187
" " on Heating of Field-magnets.. 426
Forms of Electromagnets.. 195
Formulæ for Electromagnets.. 165
Foster and Andersen's Dynamo.. 535
Foucault Currents (*see* Eddy Currents).
Foundation-ring of Armature.. 343, 461, 523, 654, 666, 676
Fracture of Connexions.. 804
Frankfort, Experiments at.. 766, 794
Frequency of Alternation.. 659, 680
Friction, of Bearings.. 116, 393
" of Air.. 116
" Magnetic (*see* Hysteresis).
Fringe of Magnetic Field.. 86, 189, 414, 437, 441
Fritsche, his Disk Armature.. 44, 547
" Theory of Winding.. 21, 302, 308, 311, 332, 547
Frölich, Dr. O.. 20, 96, 114, 118, 237, 249, 292, 584, 604
" " Formula for Electromagnet.. 166, 237
Froment's Motors.. 18, 551
Fuller-Gramme Dynamo.. 43
Fundamental Points in Design.. 46, 398, 608
" " in Motors.. 554, 759

G.

GAISBERG, von, on Armature Distortion.. 73
Ganz (*see* Zipernowsky).
Gap in Magnetic Circuit.. 149, 152, 433
Gap-space.. 63, 178, 189, 410, 433, 438, 444
" " Drag in.. 106, 554
Gaugain, J. M., on Curves of Induction.. 4, 68
Gauge of Wire, Choice of.. 356, 399, 422, 425, 817

PAGE.
Gauss's Principle.. 550
Gauze, for Brushes.. 380
General Electric Traction Company (*see* Immisch).
Generator, the Dynamo as.. 1
German-silver, used to reduce Eddy-currents.. 681
Goolden, W. T. & Co., Dynamos.............. 357, 381, 384, 393, 525, 654
" " " " Calculation of........................ 188
" " " " Tests of........................ 526, 794
" " " Regulators........................ 769
Gordon's Alternator.. 17, 667
Governing Dynamos.. 50, 278, 447
" Motors.. 503
" by Steam Pressure.. 448, 781
Governors, Automatic, Brush's.. 454
" " Dynamometric........................ 780
" " Edison's........................ 279
" " Henrion's........................ 776
" " Jamieson's........................ 780
" " Lane-Fox's........................ 777
" " Richardson's........................ 278, 778
" " Statter's........................ 478
" " Thomson-Houston's........................ 471
" " Trotter's........................ 769
" " Willans'........................ 278, 779
Gramme's Dynamos, Armature of.................. 15, 42, 343, 344, 482
" " Characteristic of........................ 254, 264
" " Potential at Collector of........................ 70
" " as Motor........................ 756
" " Multipolar........................ 482
" " Alternate-current........................ 640
" " Auto-excitatrice........................ 642
" " for Transmission of Power........................ 757
" " for Electrometallurgy........................ 538
" " Field-magnets of 197, 198, 396, 482
" " Brushes........................ 380
Greenwood and Batley's Dynamos.. 530
Grouping of Armature Windings.. 311, 326
Griscom's Motor.. 197
Gülcher's Dynamo........................... 17, 335, 344, 376, 383
" " Characteristic of........................ 298
Gyrostatic Action of Armature.. 388

H.

HAGENBACH on Theory.. 20
Haselwander's Multiphase Motor.. 714

PAGE.
Haselwander's Multiplex Transformers 752
Heat, Effects of, on Magnetism 157
" Loss of Power due to 754, 804
Heating of Armatures 353, 426, 803
" Cores 95, 98, 162, 733
" Magnets 99, 423
" Pole-pieces 98, 346
" Limit of Permissible 425, 426, 445
Hedgehog Transformer 736
Hefner-Alteneck, von, his Armature 16, 361, 545
" " " his Dynamometer 785
" " " on Transmission of Power 763
Henley's Machine 11
Henrion's Regulator 776
Henry's Motor 18, 550
Henry, The (Unit of Self-Induction) (*see* Units).
Hering, Carl, on Leakage of Magnetic Field 184
" " on Drum-winding 21, 302
Herwig on Theory 20
High Voltage, Dynamos for 474, 648, 674, 755, 766
" " Commutators for 448
" " Transformers for 737
" Pressure 474, 674, 755, 760
" Insulation 737
" Frequency of Alternation 637
Historical Notes on Dynamos 6
" " on Motors 18, 19
" " on Alternators 11, 17, 18
" " on Transformers 719
Hjorth, Sören, his Combined Dynamo 12, 59
" " his Motor 552
Hochhausen's Dynamo 198, 375
Hole-armatures (*see* Pierced Core-disks).
Holmes' Magneto Machine 11, 54, 380
Holmes, J. H., and Co., Dynamos 352, 357, 527
" " " Railway Lighting 528
Hoop Iron Cores 42, 343, 498, 654, 737
Hoopes, A., on Ewing's Theory 169
Hopkinson, Dr. Ed., on Curves of Motors 760
" " " Field-magnets of Dynamo 197, 495
" " " and Dr. J., Armature 352, 495
" " " " " on Magnetic Circuit 17, 21, 175, 185
" " " " " Alternators 662
" " " " " on Reaction of Armature 92, 436
Hopkinson, Dr. John, on Reactions in Armature 94
" " " Applications of Characteristics 249, 272
" " " Discovery of Characteristics 20, 247

PAGE.

Hopkinson, Dr. John, Reversing Gear 591
" " " on Coupling of Alternators 690
" " " Modification of Edison Dynamo 518
" " " on Magnetization of Iron 134, 135, 139
" " " on Coercive Force 159, 163
" " " on Multipolar Winding 333
" " " Drum Armature 366
Horns, or Pole-tips 81, 86, 99, 388, 488
" Driving 113, 355
Horse-power of Dynamos and Motors 110, 785
" " Calculation of 100, 405
" " Testing 785, 790
Hospitalier, E. 300, 700
Housman on Compensating Poles 441
" on Testing 791
Houston (*see* Thomson-Houston).
Hughes, D. E., his Magnetic Balance 133
Hunt, Robert, on Motive Power 552
Hutin and Leblanc's Motor 716
Hysteresis 160
" Waste of Power by 163, 164, 415, 738, 792

I.

Idle Coils 85, 453
" Wire 42, 501
Imbricated Conductors for Armatures 357, 486, 493
Immisch (*see also* Snell).
Immisch's Motor 610
" Commutator 611
" Dynamos 202, 352, 532
Impedance 629
Indicator Diagrams 161, 245, 785
Inductance 629
Induction, Process of 22, 28
" Magnetic 129, 177, 407, 422
" Curves of 66
" False 72
" Self- 84, 589, 724
" Mutual 101, 723
" Coils (*see* Transformers).
" the (or Internal Magnetization) 129, 177, 407, 422
" Rules to Remember 22, 308
" Troubles 82, 102
" " Remedy for 102
Induction-Sheath of Copper 454
Inductor Dynamos 11, 639, [illegible]

Inertia, Electric (*see* Self-Induction). PAGE.
" Magnetic 159
" Mechanical 354
Initial Magnetization 280
Instability of Magnetism 259, 263, 265
" of Arc-light 273
Instructions on Use of Dynamos 800

Insulating Materials :—
Air 375, 737
Asbestos 45, 375, 671, 688, 807
Bitumenized Paper 344
Canvas 353, 455
Cotton 357, 817
Cotton Cloth 455, 528
Ebonite 347, 383, 386, 673, 675, 679, 737, 738
Enamel 342, 353, 357, 667
Fibre, hard white 355, 489, 526
Film of Oxide 343, 357, 381
" Oil 357
Glass 672
Indiarubber 353, 611
Insulating Paint 353
Ivory 549, 550
Japan 353
Lignum Vitæ 518
Mica 45, 343, 355, 364, 375, 655, 671, 678, 804
Oil 738
Ozokerit 736
Paper 45, 342, 344, 353, 360, 364, 454, 474, 490, 518, 532, 655
" Bitumenized 344
" Manilla 353
" Paraffined 492
" Parchmentized (Willesden Paper) 353, 375, 611
" Varnished 353
Papier-maché 474
Plaster 375
Porcelain 678, 736
Rubber Varnish (Scott's) 353
Shellac 353, 357, 454
Silk 357
Slate 375
Sulphur 672
Tape 243, 357, 681
Varnish 45, 342, 357, 454
Vulcanised Fibre 353, 355, 375, 376, 384, 454, 664, 671, 678
Wood 736

Insulation of Coils, etc 353, 357, 454, 678

PAGE.
Insulation of Core-disks 43, 342, 353, 492
" of Commutator 375
" of Brush-holders 383, 384
" of Frame of Machine 803
" Testing of 784
Integration of Curves 68
Intensity of Magnetic Field 122, 812
" of Magnetizing Force of Coil 126
" of Magnetization 128, 422
Interference of Armature and Field-Magnet 74, 93, 434, 585, 653
" of Alternating Electromotive Forces 653, 704
Interior-Pole Dynamos 443, 475
Internal Characteristic 261
Iron, Importance of Quality and Quantity of 131, 143, 167, 342, 723
" Proper Cross-section of 401, 407, 422
" Cast 141, 143, 145, 149, 407, 494
" Magnetic Properties of 139
" Permeability of 129, 408
" Saturation of 131, 166
" Wire for Cores 45, 46, 342, 361, 503, 506, 733, 736
" Wrought, Properties of 140, 142, 144, 146, 148, 149
Iron-clad Dynamos 200
Isenbeck, Dr. Aug., Researches by 68
Isthmus Method of Magnetizing 148

J.

JABLOCHKOFF, P. 719
Jacobi's Motor 18, 20, 549
" Law of Electromagnet 165
" Law of Maximum Activity 552, 559, 561
" Commutator 9, 549
" Electric Boat 549
" Magneto-Machine 9
Jamieson's Electric Governor 781
Jamming of Armature 803
Jehl and Rupp, Disk Dynamo 45, 543
" " Continuous-current Transformers 750
Joel's Dynamo 197, 343
Johnson and Phillips (Kapp's Dynamos 393, 488, 654
" " " Oil Insulators 766
Joints in Magnetic Circuit 152, 195
Joyce, on Heating of Layers 429
Joubert, J., on Induction of Armatures 73
" " on Self-induction 94
" " on Speed of Machines 118, 225
" " Theory of Alternators 20, 62

PAGE.
Joule, J. P., on Electric Motor 20, 549
" " Form of Electromagnet 170
" " Law of 165, 170
" " on Magnetic Saturation 131, 148
Journals Proper proportions of 389
"Jumbo" Dynamos 514
Jürgensen's Dynamo 198

K.

KAPP, Gisbert (*see* Crompton and Kapp).
" " Dynamos 200, 355, 384, 397, 423, 487
" " Alternator 386, 654
" " on Compound Winding 286, 300
" " Formula for Electromagnet 165, 173, 175
" " Transformers 738
" " Graphic Diagram for Motors 762
" " Pre-determination of Characteristic 21
" " on Series Motor 582
" " on Capacity and Size 119
" " Design of Shaft 392
" " Bearing of Alternator 393
" " Rules for Weight and Depth of Winding 425
" " Surface needed for Cooling 429
" " Load Curves 435, 654
" " on Limiting Load of Armatures 439
" " Electric Transmission of Power 568, 764
" " Forms of Field-Magnets 200, 489
" " Multipolar Windings 326, 369, 489
" " Segmental Core-disks 343, 489
" " Mode of Driving Core-disks 351
" " on Coupling Alternators 697
" " Method of Testing Horse-power 790, 793
Kelvin, Lord (see Thomson, Sir William).
Kennelly, on Cross-magnetization 91
" on Magnetic Reluctivity 169
Kennedy, R., Iron-clad Dynamo 200, 506
" Single-coil Dynamo 202, 506
" Alternators 642, 645, 686
" Transformers 720
" Regulating Alternators 747
Kerchove and Co.'s Engines 510
Keys for Driving Armature 347, 351, 396
Kingdon's Alternator 11, 684
Kirchhoff's Researches 134
Kohlrausch, W., on Lahmeyer's Dynamo 73, 529
Koosen, J. H., on Theory 20
Kuhn's Engines 512

L.

PAGE.
LADD, W., his Machine 14, 54
Lag, alleged Magnetic 88, 102, 159, 165
Lag of Current behind Electromotive-force 630, 637
Lahmeyer's Dynamo 185, 200, 202, 529
Lamination of Cores and Pole-pieces 45, 96, 342, 346
  " of Field-Magnets 295, 532, 683
  " of Motor-Magnets 702
  " of Armature Conductors 96, 357, 401
Lamont's Formula for Electromagnet 166
Lane-Fox, Continuous Current Transformers 720
Langley, J. W., Magnetic Shunt 769
Lap-winding of Armatures 311, 646
Lauckert 61
Lauffen, Experiments on Transmission at 688, 708, 713, 766
Laurence, Paris, and Scott, Dynamos 326, 346, 347, 369, 528, 612
  " " " " Motor Dynamos 749
Law of Electromagnet 165
 " " Lenz 20
 " " Ohm 23
 " " Action and Reaction 589
 " " Alternate Current Flow 627, 632
 " " Magnetic Circuit 171, 177, 409
Lead of Brushes 79, 83, 86, 436
 " " " negative, in Motors 92, 436, 586
Leakage, Magnetic 180, 182, 477, 723, 744
  " " Coefficient of 182, 408, 434
Least-speed of Self-excitation (*see* Critical Speed) 51, 784
Leblanc (*see* Hutin).
Ledeboer on Coupling Dynamos 798
Leduc on Magnetization 152
"Leeds" Dynamo (*see* Greenwood and Batley).
Length of Armature, proper 98, 401, 403, 431, 440, 444, 654
  " " Wire for Winding 423
Lenz, Law of Induction 20, 589
  " and Jacobi (*see* Jacobi).
Le Roux, Theoretical Investigations 20
Lightning Arresters 803
Limit of Magnetization 148, 422
 " " Non-sparking Load 436, 439
 " " Permissible Heating 425
Line, Neutral 83, 587
Lines of Magnetic Force 22, 122, 812
Load-curves 435
Lodge, Oliver J., Calculation of Fluctuations 218
  " " on Spurious Resistance 95

PAGE.

Lodge, Oliver J., on Law of Motors 568
Long-shunt 60, 289, 795
Lontin's Dynamos 16, 44, 54, 200, 644
Lorenz (*see* Jürgensen).
Loss of Magnetism 259, 263, 265, 806
Losses, Testing the separate 791
Lost Amperes (in shunt) 238, 404, 791
  “ **Volts** 227, 277, 404, 791
Lubrication of Commutator 802, 806
  “ “ **Bearings** 394, 675, 682
Lubricators 395, 469, 675, 682

M.

MAGNETIC Principles 121, 170
  “ Shunt 50, 186, 769
  “ Discontinuity 343
  “ Lines of Force 122, 812
  “ Circuit 17, 170, 400, 738, 784
  “ Creeping 88, 165
  “ Field 24, 105, 122, 813
  “ Flux, the 47, 176, 400, 406
  “ Induction, Coefficient of (*see* Permeability).
  “ Units 121, 811
  “ Intensity 122, 126, 813
  “ Polarity 123
  “ Potential 438
  “ Permeability 129, 148
  “ Pull on Armature 388, 433
  “ Reluctance 176, 409
Magnetism, Instability of 259, 263, 265
  “ Permanent 49, 253, 267, 296
  “ the Unit of 121, 810
Magnetization 128
  “ Curves of 132
  “ Resultant 79
  “ Saturation of 131, 408
  “ Methods of 49
  “ Residual 49, 158, 253, 267, 296
Magnetizing Power of Coil 124, 409, 411
  “ “ of Shunt 428
  “ “ of Series Coil 428
Magnetometer 133
Magneto-motive Force 124, 171, 409
  “ “ Calculation of 409, 411
  “ “ in Gap-space 438
Magnolia Metal 393

PAGE.

Magneto-electric Machine (Magneto-dynamo).................... 49, 224

" " Characteristic of........................ 231, 577

Magnets (*see* Field Magnets).

Malderen, Van, his Machines.. 11

Management of Dynamos.. 795

" **Manchester" Dynamo** (*see* J. and E. Hopkinson).

Maquaire's Regulator.. 508

Martin and Wetzler on Motors.. 614

Mascart's Investigations.. 20, 118

Masson's Researches.. 11

Mather and Ayrton on Rheostats.. 771

Mather and Hopkinson's Dynamo................................ 201, 495

Mather and Platt, Dynamos.......................... 201, 366, 396, 495

" " " Iron used by.................................. 139, 140

" on Compensating Armature Reaction........................ 93

Maximum Magnetization.. 131

Maximum Permissible Current........................ 399, 405, 428

Maxwell, J. Clerk, his Investigations...................... 20, 171, 550

" " " on Rule of Polarity.............................. 123

McTighe's Dynamos.. 202

Mèchanical Characteristics.................................. 574, 584

Mechanical Principles.................................. 104, 387

" " Details of Design.............................. 387

" " Reactions in Dynamo.................. 104, 113, 638

" " " in Alternator.................. 113, 617

Meyer and Auerbach's Researches.. 20

Mines, Lighting of.. 293

Mitis Metal.. 149

Moncel (*see* Du Moncel).

Mordey, W. M., Method of Multipolar Connecting.................. 333

" " and Watson, on Compounding.................... 605

" " Alternator.............................. 205, 676, 683

" " Transformers.............................. 735

" " on Distribution of Potential.................. 69, 73, 497

" " Improvements in Schuckert Dynamo............ 17, 497

" " on Commercial Efficiency.......................... 681

" " on Coupling of Compound Dynamos.................. 707

" " " of Alternators........................ 697

" " on Curve of Electromotive-force.................... 70

" " Iron-clad Magnet.............................. 202

" " on Eddy-currents in Motors........................ 589

" " on Shunt Motors.............................. 583

" " on Governing Motors.............................. 606

" " on Losses by Hysteresis.................. 164, 739

" " on Relation of Speed and Volts.................... 225

" " Flexible gauze collectors.......................... 386

" " Design of Shaft.............................. 392

PAGE
Moment, Magnetic 130
" of turning (*see* Torque).
Morin's Dynamometer 785
Motor-Generators, or Motor-Dynamos (*see* Transformers, Continuous-current).

Motors of various Inventors :—
- Andersen and Girdlestone (" Agir ") 384, 612
- André 596
- Atkinson 614, 707
- Ayrton and Perry 609
- Borel 703, 715
- Bourbouze 550
- Brown 491, 612, 713
- Brush 595
- Curtis, Crocker, and Wheeler 616
- Cuttriss 616
- Dal Negro 18, 550
- Davenport 18
- Davidson 18, 552
- Deprez 594
- Dobrowolsky 707
- Ferraris 703, 715
- Froment 18, 551
- Goolden 615
- Gramme 757
- Henry 18, 550
- Hjorth 552
- Hopkinson 616
- Hutin and Leblanc 716
- Immisch 610
- Jacobi 18, 549
- Joule 549
- Leblanc (*see* Hutin).
- Mordey 702
- Pacinotti 18
- Page 18, 550, 552, 617
- Perry (*see* Ayrton and Perry).
- Reckenzaun 609
- Ritchie 18, 549
- Schallenberger 715
- Siemens 617, 715
- Sprague 596, 602, 614
- Sturgeon 550
- Tesla 703
- Thomson-Houston 616
- Trouvé 551, 616, 702
- Wheatstone 18, 551
- Wheeler 616

PAGE.
Motors, Theory of 556, 576
“ Efficiency of 557
“ Government of 591
“ Lead of Brushes of 86, 587, 590
“ Must have more powerful Magnets 491, 588, 616, 755, 759, 766
“ Brushes for 381, 384
Mountain, W. C., Design of Commutator and Brush-holders 383
Müller's Formula 165
Multiphase Currents 642, 687, 703, 766
“ Alternators 687
“ Motors 703
Multipolar Dynamos 17, 437, 442, 501, 510, 516, 523, 533, 640
“ “ design of 442, 640
“ “ Armatures for 310, 333, 510
“ “ Field-magnets of 201, 203, 510, 523, 640, 689
“ Series Winding 311, 326, 335, 487, 489
Munich, Tests at 244, 756, 794
Municipal Lighting 448, 477
Murray on Self-excitation 13
Murray's Tests of Dynamos 464, 788, 794

N.

Name “Dynamo-electric” 1, 14
Negro (*see* Dal Negro).
Neutral Points 71, 79, 82, 315, 381, 587
Neumann's Theoretical Investigations 19
Newton F. M., Dynamo 479, 532
Niaudet, Alfred 4
“ “ his Armature 544
“ “ on Gramme Dynamo 482
Nicks to stop Sparking 441, 539
Noise in running 807
Nollet's Machine 11
Notation, Algebraic 208

O.

Ohm, Dr. G. S., Law of 23, 171, 626, 813
Ohm, the Unit of Resistance 814
Oil, as Insulator 732, 766, 817
Oil Insulators 766
Oil, Supply of, under pressure 395, 675, 682
One-coil Magnet 202, 530
Open-coil Dynamos 17, 449, 473
Organs of Dynamos 2, 31, 34
Oscillatory Dynamos and Motors 17, 550, 617
Output of Dynamos 100, 398, 815

PAGE.
Output of Dynamos in relation to size......... 117, 398, 440, 443, 608, 654
Over-compounding..... .... 293, 295, 501, 751, 766
Overhung Pulley.. 391
" Armature.. 510, 675
" Field-Magnet... 689

P.

PACINOTTI'S Dynamo and Motor.............................. 14, 19
" Armature.................................. 14, 16, 346
" Commutator.. 14
" Disk Dynamo................................. 338, 545
Page's Motors.. 550, 617
" Early Magneto-machine................................ 11
Paper (*see* Insulating Materials).
Parallel, Coupling of Dynamos in............................ 693, 796
" " of Coils in............................ 315, 500, 673
Paris and Scott (*see* Laurence).
Parsons, Brush-holder.. 385
" Alternator.. 676
Patent Office, United States, its wisdom........................ 727
Paterson and Cooper's Dynamos (Phœnix).................. 492, 538
" " " " Data of...................... 416, 493
" " " " Calculations about................. 418
" " " " Armature of...... 348, 355, 396, 416, 492
" " " " Field Magnets of...... 197, 201, 417, 493
" " " " Commutator of................ 376, 384
" " " " Arc-Lighting......................... 477
" " " Alternator.......................... . 201, 662
Pedestals... 392, 397
Perforated Core-disks................................ 346, 487, 490, 688
Peripheral Speed................................ 119, 357, 421, 675, 676
Permanent Magnets.. 49
" Magnetism in Characteristic...................... 253, 267, 290
Permeability of Iron...................................... 129, 138
Permeameter.. 138
Permeance (Magnetic Conductance).................................. 186
Perry, John (*see* Ayrton and Perry).
" his Dynamo.. 545
" Self-regulating Combinations................................... 58
" Method of Winding Armature............................ 326, 337
" on Bending Moment of Shafts................................. 391
" on Transformers....................................... 743, 744
Perturbations due to Masses of Iron..... .... 98, 180, 183
Pescetto, on Capacity.. 118
Petrina's Commutator... 9

PAGE.
Peukert's Investigations 93, 747
Phase of Alternation 620, 642, 690
"Phœnix" Dynamo (*see* Paterson and Cooper).
Phosphor Bronze, use of 355, 374
Physical Theory of Dynamo 22
Pierced Core-disks 346, 357, 487, 490, 688
Pilot brush, investigation by 69, 774
" lamp 801
Pitch, of Poles 314, 650
Pixii's Dynamo 8
Plücker's Unipolar Machine 542
Poggendorff, J., on Theory 20
Poggendorff's Commutator 9
Point, Diacritical, of Semi-saturation 166, 446
" Dead, of Motor 705
" Neutral 71, 79, 82, 315, 381, 587
" " Shifting of 79
Polarity, Magnetic 123
" Reversal of 51, 52, 276, 537
Polar-span, angle of 79, 406, 437
Pole-armatures 41, 44, 644
Pole-pieces 198, 656
" Form of 87, 103, 198, 357, 489, 495, 521, 592, 656
" Eddy-currents in 98
" Heating of 98
" Internal 475
Pole-surfaces, shaping of 72, 87, 103, 198, 357, 478, 521, 526, 592, 656
Pole-tips of Cast Iron 388
" " Reversing Field at 86, 438
Poles 122, 198
" Consequent 198, 482
" Salient 198, 482
" Resultant 79
Polechko's Disk-dynamo 479, 547
Pollard, J., Experiment by 782
Polyphase Currents (*see* Multiphase).
Potential, Curves of Distribution of 68, 461
" Constant, Combinations for 56
" " Distribution with 277
" Difference of, at Terminals 226
Power, a product of two Factors 107, 109, 572
" Electric Transmission of 753
" Required to drive Dynamo 2, 110
" of Motor 572, 608
" Methods of Measurement of 785
" Unit of, the *Watt* 816
Practical Units of Measurement 809

PAGE.

Predetermination of Curves of Dynamo 175, 180, 419
Pressure on Bearings 387
Principles, Fundamental, of Dynamo 1, 22, 212
" of Reversibility 1, 18, 608
" of Alternate Currents 618
" of Motors 554, 557
" of Transformers 721
Prony's Brake 786
Propelling Drag in Motor 554
Pulleys 391, 396
" used for Sliding Contact 386, 689
Pulsating Motors 616
Puluj, on Continuity of Currents 214
Pulvermacher on Lamination of Cores ....

Q.

Quad, or Quadrant, the (Unit of Self-induction), (*see* Henry).

R.

RACING of Motors 593
Racking of Armature Conductors 113, 379, 638, 806
" " Connecting Pieces 379, 804
Radian (Unit of Angle) 109
Raffard's Gramme Dynamo 352
" Brake 787
Railway, Electric, Machinery for 522
Ravenshaw (*see* Goolden) 776, 790
Raworth, on Induction in Armatures 73
Raworth's Coupling 393
Rayleigh, Lord, on Electric Testing 783, 790
Reactions of Armature and Field-magnet in Dynamo. 62, 74, 113, 434, 617
" " " in Motor 585
" Mechanical, in Armatures 113, 379, 638
Rechniewski's Investigations 118
Reckenzaun's Motor 591
Rectified Currents (*see* Redressed Currents).
Redressed Currents 38, 212, 452, 652, 659
Regulating properties of Series Dynamos 51, 581
" " of Shunt Dynamos 53, 606
Regulation, Automatic (*see* Governors).
" by shifting Brushes 278, 469, 478, 768
" by introduction of Resistance 53, 278, 768
" by Exciting Circuit 768
" by third Brush 53, 773

Regulators (*see* Governors). PAGE.
Reignier's Investigations 763, 777
Reluctance of Magnetic Circuit 176, 409, 445
Remanence 159
Repairs, execution of 361, 467, 659, 802
Residual Magnetism 158
Resistance 23, 783, 784, 813
“ per cubic inch of Winding 430, 818
“ of Coil of given Volume 423
“ of Dynamo 226
“ critical 51, 259, 261, 264
“ spurious, of Armature 94, 629
“ in the Characteristic 257, 258
“ Unit of, the *Ohm* 814
“ Insulation 784
“ Magnetic (Reluctance) 176, 406, 445
“ for Regulating 279, 447, 769
Retardation of Phase of Alternate Currents 627
“ “ “ in Transformers 730
Reversal of Polarity 51, 52, 276
“ of Current at Commutation 85, 87, 436, 441, 587
Reversibility, Principle of 1, 18
Reversing Gear 590, 593
Rewinding Dynamos 259, 398, 423, 436
Rheostat (as Regulator) 279, 769, 771
Ribbon Cores, when used 45, 98, 342, 461
“ Copper, for winding 356, 671, 681, 817
Richardson's Governor 778
Richter, Ernest, on Siemens' Dynamos 299
“ “ on Difference of Potential 228
Ring Armatures 36, 41, 42, 302, 358, 482, 640
“ “ How to Wind 358, 640
“ “ External 360, 510
Ring Winding, Developed Diagrams of 309
“ “ Practical Method of 358
Ritchie's Motor 549
“ Magneto-machine 8, 9, 11
“ Induction Coil 719
Robin's Dynamo 546
Rocker's 83, 383, 384
Rocking of Brush-holder 87, 802
Rotatory Brushes 380
“ Currents 710
“. Field Motors 703
Rowland, Henry A., on Magnetism 134, 148, 171, 173, 195
Rücker, A. W., Limit of Self-regulation 21, 287, 300
Ruhmkorff, Winding of Armatures 54
Ruhmkorff Induction Coil 719

PAGE.
Rules for Design and Construction................ 243, 355, 404, 421, 608
" " Armatures (*see* Armatures).
" " Field-magnets (*see* Field-magnets).
" " Resistances.................................. 243, 244, 653
" " Compounding.................................. 294, 412, 603
" " Winding.................................. 422
" " Lamination.................................. 96
" " Constructing Transformers.................................. 722
Rupp (*see* Jehl).
Ryan, on Curves of Armature-reaction.................................. 73
" on Transformers.................................. 731

S.

Salient Poles.................................. 198, 482
Satural values.................................. 166
Saturation, Magnetic, Effects of.................................. 131, 132, 166
" " Curve of.................................. 132
" " Formulæ for.................................. 165
" " Diacritical Point of.................................. 166, 446
Sawyer's Dynamo.................................. 11, 200
Saxton's Machine.................................. 9
Sayer's Disk Dynamo.................................. 546
" Electro-plating Dynamo.................................. 539
" Nicks to stop Sparking.................................. 441, 539
Schellen, H. 4
Schorch's Dynamo.................................. 202
Schuckert's Dynamos.................................. 523
" " Multipolar.................................. 17, 523
Schuckert-Mordey Dynamo.................................. 204, 497
Schültze, on Cross-magnetization.................................. 91
Schuyler's Dynamo.................................. 478
Scott, Ernest, and Mountain.................................. 383, 529
" (*see* Laurence).
Scott's Rubber Varnish (*see* Insulating Materials).
Secohm (*see* Henry).
Secohmmeter.................................. 816
Sections, Armatures wound in.................................. 40, 64, 400, 640
" Field-magnet Coil in.................................. 617
Segmental Core-disks.................................. 343, 360
Segments, or Bars of Commutator.................................. 64, 374
Self-exciting Principle.................................. 10, 12, 14, 51, 263, 652, 784
Self-governed Motors.................................. 597
Self-induction.................................. 23, 83, 94, 102, 214, 474, 478, 653, 724, 816
" Coefficient of.................................. 478, 623, 724, 817

PAGE.
Self-induction, produces Lag 627
“ Unit of 817
Self-regulating Dynamos 57, 270, 280, 747
Sellers's Double Lubrication 395
Sellon, R. P 721
Separate-circuit Dynamo 53
“ “ Motor 605
Separately-excited Dynamo 49, 50, 224, 230, 231, 652
Series, Coupling Dynamos in 690, 795
Series Dynamo 51, 236, 271, 581, 772, 796
Series-grouping of Armature Windings 311, 316, 326, 487, 489
Series Lighting, Dynamos for 448
Shaft, proper design of 350, 390, 392
Shaping of Pole-pieces 72, 87, 103, 198, 357, 478, 521, 526, 592, 656
Shifting of Neutral Points 79
“ of Brushes 83, 86, 384, 768, 802
“ Brushes for Regulating 278, 470, 476, 768
Short Circuit 86, 803
“ “ Magnetic 198
Shunt Dynamo 52, 238, 261, 271, 583
Shunt, Magnetic 50, 186, 769
Shuttle-wound Armature 12, 33, 552
Siemens, Dynamo (old) 16, 34, 197, 537
“ “ (new) 506
“ “ Field Magnet of 197, 200, 507
“ “ Winding of Armature 361, 508
“ “ Alternator 16, 203, 388, 664
“ “ for Electroplating 362, 537
“ “ Unipolar 542
“ “ New Types 200, 201, 509
“ “ Compound, Winding of 507
“ “ Characteristics of 246, 251, 262
“ “ Bearings of 393
Siemens, Alexander, on Torque of Motors 580
“ “ Graphic Constructions 700
Siemens, Sir William, Efficiency of Motors 561
“ “ Early Researches 12, 17
“ “ on Transmission of Power 560, 582
“ “ on Shunt Dynamo 262
“ “ on Instability of Arc Light 273
“ “ on Compound Winding 61
Siemens, Werner, von, on Magnetism 167, 168
“ “ Self-exciting Machine 13
“ “ on Cross-magnetization 91
“ “ Shuttle-wound Armature 12, 33, 537
“ “ Invents Name of Dynamo 14
Siemens, Werner, von, on Transmission of Power 560

PAGE.
Siemens and Halske's Ring Dynamo 201
" " " Internal-Pole Dynamos 201, 360, 421, 443, 510
" " " Brush-holder 385
" " " Continuous-Alternating Transformer 751
" " " Multiphase Motors 714
Silver Solder 364, 665
Sines, Curve of 66, 214, 619, 620, 634
Single-coil Dynamo 202, 530
Sinsteden's Early Improvements 11, 20, 61
Size, proper, of Wires to carry Currents 422, 473, 817
" in relation to Output 117, 272, 608, 654
Sleeve, for Armature 350, 392
Sliding Contacts 373, 386, 542, 550, 648, 689
Sliding Rails 800
Slow-speed Machines 260
Smith, Frederick J., Dynamometer 232, 781, 785
" " Testing Motors 788
Smith, Holroyd, Brushes for Motors 593
Smith, Willoughby, Induction Experiment 543
Snell, Albion, T., Carbon Brushes 382, 532
" " Dynamo 532
" " Design of Motors 588, 608, 612
" " on Output and Size 440, 443, 608
Snell and Kapp's Transformer (*see* Kapp).
Soft-metal for Bearings 393
South London Electric Railway 522, 616
Spacing, the, in Winding Armatures 315
Span, Polar, Angle of 79, 403, 437, 650
Sparking, Cause of 83, 587
" Prevention of 86, 87, 435, 539, 588, 802, 804, 806
" Load Limited by 87, 435
" in Motors 588
Speed, Dependence of Volts on 22, 46, 225, 405, 626
" Advantage of High 48, 560
" Critical, of Dynamo 261, 282, 544, 784
" " of Motor 600
" in relation to Power 109, 572
" Peripheral 19, 357, 421, 675, 676
" in relation to Cooling 429
Sperry's Arc-light Dynamo 475
Spherical Armature 464, 473
Spherical-seated Bearings 393, 525, 675
Spiders for Armatures 347, 353, 392, 485, 492, 526
Spiral Winding 311
Spokes for Armature 347
Sprague, F. J., Motors 556, 614

PAGE.
Sprague, F. J., Tests of Dynamos.................................. 794
" " on Regulation of Motors.................................. 596
Spurious Resistance.................................. 94, 629
Square Wire, use of.................................. 344, 356, 357, 402, 498, 518, 817
Stafford and Eaves's Dynamo.................................. 538
Stamping Core-disks.................................. 343
Stanley's Alternator.................................. 643, 657, 686
Statter, J. G., Arc-lighting Dynamo.................................. 202, 478
" " Governor.................................. 478
Steel, Use of, in Dynamo.................................. 49, 481, 689
" Magnetic Properties of.................................. 11, 132, 157
Step-up Transformers.................................. 766
Stöhrer's Dynamo.................................. 9
Stoletow's Researches.................................. 134, 167
Storch on Capacity.................................. 119
Stove, Drying Armature in.................................. 358, 376
Stranded Wire Conductors.................................. 357, 401, 489, 493, 666, 817
Stray Power, the.................................. 116, 790
Stress, Effects of on Magnetism.................................. 156
Stroh, A.................................. 14
Strömberg, on Demagnetization.................................. 91
Sturgeon's Commutator.................................. 9
" Disk.................................. 550
" Magneto-machine.................................. 9, 33
Susceptibility, Magnetic, of Iron.................................. 129, 130
Swan, Joseph W.................................. 61
Swinburne, James (*see* Crompton-Swinburne).
" " on Compound Winding.................................. 61
" " on Testing Power.................................. 709
" " on Transformers.................................. 476
" " on Potentials at Commutator.................................. 73
" " on Magnetization of Iron.................................. 137
" " on Chord Winding.................................. 304
" " Pierced Core-disks.................................. 347
" " on Armature Interference.................................. 433
" " on Auxiliary Reversing Pole.................................. 441
Swivel Bearings.................................. 383, 525, 675
Symbols, List of.................................. 208
Symmetry, Necessity for.................................. 195, 361, 432
Synchronism, Conditions of.................................. 699
Synchronizer.................................. 698
Synchronous Motors.................................. 700

T.

TAPE (*see* Insulation).
Tape, Copper (*see* Ribbon).

PAGE.
Tatham's Dynamometer........ 787
“Taunton” Dynamo (*see* Newton).
Teazer Circuit........ 59
Teeth on Armature........ 15, 42, 346, 357, 492, 528, 530, 659
Temperature, Rise of (*see* Heating).
Terminals, Volts at........ 226, 253
Tesla, Nikola, Rotatory Field Motors........ 19, 703, 707, 708
“ “ on High-period Alternations........ 637
Testing Dynamos and Motors........ 783
Tests of Brush Dynamo........ 464
“ on Transmission........ 756, 767
Theory of Dynamo, Physical........ 22
“ “ Algebraic........ 207
“ “ Geometrical........ 245
“ “ Alternate-current........ 618
“ “ Series-wound........ 236
“ “ Shunt-wound........ 238
“ “ Compound-wound........ 281
“ “ History of........ 19
“ “ Recent Advances........ 20
“ Motors........ 19, 561, 574
“ Transformers........ 740
“ Transmission of Power........ 753
“ Armature-Winding........ 301
Third Brush, Regulation by........ 53
Thompson, Milton E., on Armature Induction........ 73, 474
Thomson-Houston Dynamo........ 17, 464
“ “ “ Armature of........ 466
“ “ “ New Ring Armature........ 467
“ “ “ Automatic Regulator........ 471, 773
“ “ “ Commutator........ 469
“ “ “ Air-Blast........ 472
“ “ “ Field-magnets........ 199, 464
“ “ “ for Incandescent Lamps........ 473
“ “ “ Magnetic Leakage of........ 184
“ “ “ Induction Curves of........ 73
Thomson, Elihu, Dynamometric Governor........ 781
“ “ Alternate-current Motors........ 702
“ “ Automatic Regulator........ 471
“ “ on Transformers........ 747, 750
“ “ on Phase Indicator........ 699
“ “ Oblique Compensating coil........ 93, 294
“ “ Alternators........ 201, 659, 686
“ “ on Transmission of Power........ 560
Thomson, James, on Term Torque........ 108
“ “ his Dynamometer........ 787
Thomson, Sir William, Alternate-current Dynamo........ 17, 649, 668

PAGE.

Thompson Sir William, Rotating Brushes 380
“ “ Rules for Winding Dynamos 21, 240, 242
“ “ Step-down Dynamo 560
“ “ Theory of Unipolar Dynamo 544
“ “ on Motive Power 560
“ “ Wheel Dynamo 479, 547
“ “ on Gyrostatic Action 388
“ “ on Transmission of Power 560
“ “ Law of Similar Electromagnets 430
Thomson, Joseph J., on Magnetic Joints 153
Three-dynamometer Method 633
Three-phase Alternators 687, 688
“ “ Motors 708
Three-voltmeter Method 633
Three-wire System of Distribution 750
Thurston, on Brush Dynamo 464
Thury's Dynamo 201, 331, 534
Time needed for Compounding 295, 521
Toothed Armatures 15, 42, 346, 357, 493, 528, 659
Torque 108, 110, 114, 572
Total Characteristic 266, 267
Traction Method of measuring Permeability 137
Tramway, Dynamos for 295, 521
Transformers, Use of in Distribution 717
“ Alternating, Deprez and Carpentier's 720
“ “ Gaulard and Gibb's 720
“ “ Ferranti's 721, 737
“ “ Kapp and Snell's 721, 733, 738
“ “ Mordey's 721, 735
“ “ Swinburne's 721, 736, 738, 747
“ “ Westinghouse's 721
“ “ Zipernowsky 733, 747
“ “ Construction 733
“ Commuting 750
“ Continuous-current 748
“ Continuous-alternating 751
“ Historical Notes on 719
“ Theory of 721, 740
Transmission Dynamometer 787
“ of Power 568, 581, 753
Transversal Electromagnet 15
Trimming Brushes 380, 801
Trotter, A. P., on Magnetic Leakage 184
“ “ his Regulator 776
Trotter (*see* Goolden).
Trouvés Motor 551
Turning-moment (*see* Torque).

PAGE.

Twisted Conductors on Armature ... 357, 486
"Tyne" Dynamo (*see* Ernest Scott and Co.).
Types of Armatures ... 41, 640
  " of Field-Magnets ... 195

U.

UNBUILDING (*see* Magnetism, Instability of).
Unipolar Dynamos ... 6, 542
Uni-pole-piece Dynamo ... 477
Unit of Electromotive-force ... 210, 809, 814
  " of Magnetism ... 811
  " of Output (Board of Trade Unit) ... 816
United States Patent Office, its Procedure ... 727
Units, System used by Electricians ... 809
Uppenborn ... 300, 543
Upton, C ... 513
Use of Dynamos, Instructions for ... 800
Useful points in Designing ... 421, 425, 429, 436, 608, 650, 654

V.

VAN de Poele's Dynamo ... 198
Van Malderen (*see* Malderen).
Variable Resistance (*see* Rheostat).
Varley, Cromwell F ... 214, 380, 719
Varley, Octavius and Frederick ... 13, 45
Varley, S. Alfred, Unipolar Dynamo ... 542
  " " Electromagnet Machines ... 13
  " " on Self-excitation with ... 13
  " " on Permanent Magnets ... 13
  " " on Double-wound Machine ... 13
  " " Claims Compound Winding ... 61
Velocity (*see* Speed).
Ventilation of Armature ... 203, 347, 349, 353, 443, 461, 489, 495, 501, 514, 672, 681
  " Commutator ... 375, 472
  " Field-magnets ... 507
Vibration to be avoided ... 354, 805, 807
  " Effects of on Magnetism ... 157, 164
Victoria Dynamo (*see* Schuckert-Mordey).
Vincent, C. W. (*see* Elphinstone and Vincent).
Virtual Amperes and Volts ... 631, 632, 812, 813
Viscous Hysteresis ... 88, 165
Volt, the, Unit of Electromotive-force ... 210, 809
Volt-ampere (*see* Watt).
Volts at Terminals ... 226, 253
Volume in relation to Output ... 440, 609, 654

PAGE.
Von Ettingshausen (*see* Ettingshausen).
Von Siemens (*see* Siemens).
Von Hefner-Alteneck (*see* Hefner-Alteneck).
Von Waltenhofen (*see* Waltenhofen).
Vulcanized Fibre, Use of (*see* Insulating Materials).

W.

WALENN, on Reversibility 19
Wallace-Farmer Dynamo 545
Waltenhofen, A. Von, Theoretical Researches 20
“ “ on Law of Electromagnet 165
Warburg, on Cycles of Magnetization 161
Waste Magnetic Field 98, 182, 189, 194
Waterhouse's Regulator 773
Watkins' Machine 8
Watson and Mordey (*see* Mordey).
Watt, the, Unit of Electric Activity or Power 109, 233, 249, 427, 815
Watts wasted 163, 405, 415, 425, 427, 526, 680, 689, 739, 791
Wave-winding of Armatures 311, 649, 661, 670, 687
Weak Magnets, result of 87, 588
Wearing of Commutator 374, 802
Webber, on Continuous-current Transformers 749
Weber, H. F., Tests of Transmission of Power 759, 767
Weber, Wilhelm 542
Weight of Wire for Winding 423, 425
Wenström's Method of Winding Armatures 347, 535
“ Dynamo 200, 535
Westinghouse's Alternator 201, 393, 657
“ Transformer 735
Weston's Dynamo 17, 43, 348, 355, 537
“ “ Field-magnets of 197
Wetzler (*see* Martin and Wetzler).
Weymouth, on Drum-Winding 302
Wheatstone's, Sir Charles, Shunt Dynamo 14
“ “ Motors 551, 586
“ “ Early Improvements 9, 11
“ “ Self-exciting Principle 13
Wheel Dynamo, Thomson's 479, 545
“ “ Polechko's 547
Wheeler's Motors 616
Whirl, Magnetic, surrounding Conductor 27
Wilde's Dynamos 11, 12, 17, 50, 54, 195, 201, 203, 537, 646
“ Researches on Coupling of Dynamos 689
Wilke, A., on Berlin Dynamos 510
Willans' High-speed Engines for Central Stations 523, 526, 668
“ Magnetic Clutch-coupling 397
“ Electric Governor 779

Willesden-paper (*see* Insulation). PAGE.
Winding, Rules for, of Armatures 301, 356, 362, 399, 423
" " " Field-magnets 240, 259, 423
" " " Motors 491, 603, 608
" Diagrams 307, 359, 687
" Tables 305, 313, 321, 324, 329
Winkler's Dynamo 55
Wire, Iron, used for Armature Cores 45, 343, 503, 506
" " for Transformer Cores 733
" " wound over Armatures 346, 530
" Copper, for Winding 356, 399, 422, 425, 817
Wire for Binding (*see* Binding Wires).
Wodica's Winding of Armatures 317
Wood's Arc-light Dynamo 476
" " Regulator 774
Wood, used for Distance-pieces 346, 362, 363, 367, 655
" " " Driving-horns 349, 355
Woolrich's Electroplating Dynamo 9, 536
Work done by Conductor in Field 127, 554
Wright and Kapp 286

Y.

YOKE, Magnetic 195

Z.

ZICKLER, C., on Compound Winding 300
Zig-zag Winding (*see* Wave-winding).
Zinc, Cost of, for Motive Power 553
" Used for Footsteps 184, 415, 515, 520
" Used for Coil-frames 664
Zipernowsky's Dynamos 201
" Alternator 644, 662
" Method of Compounding 747
" Transformer 733

Plate xvi

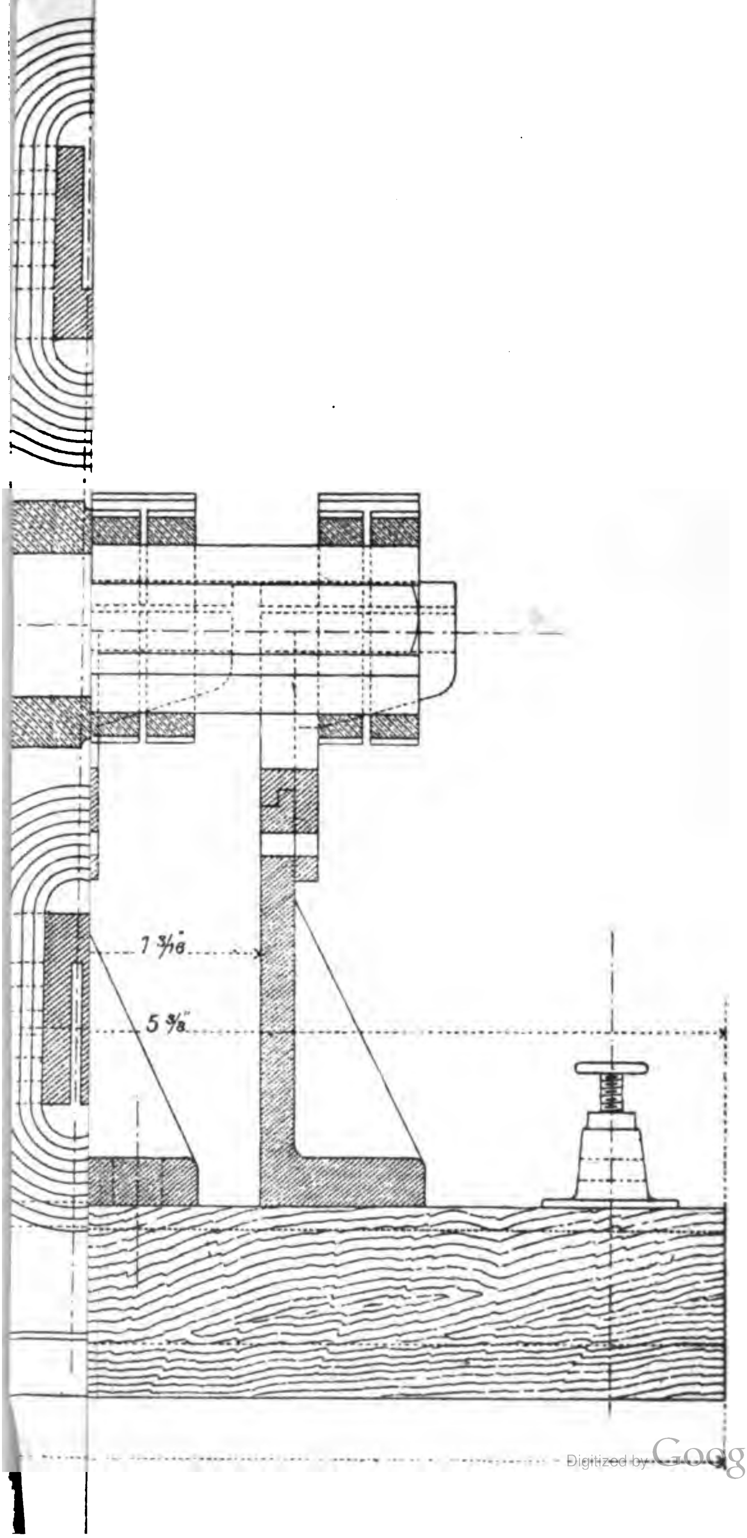
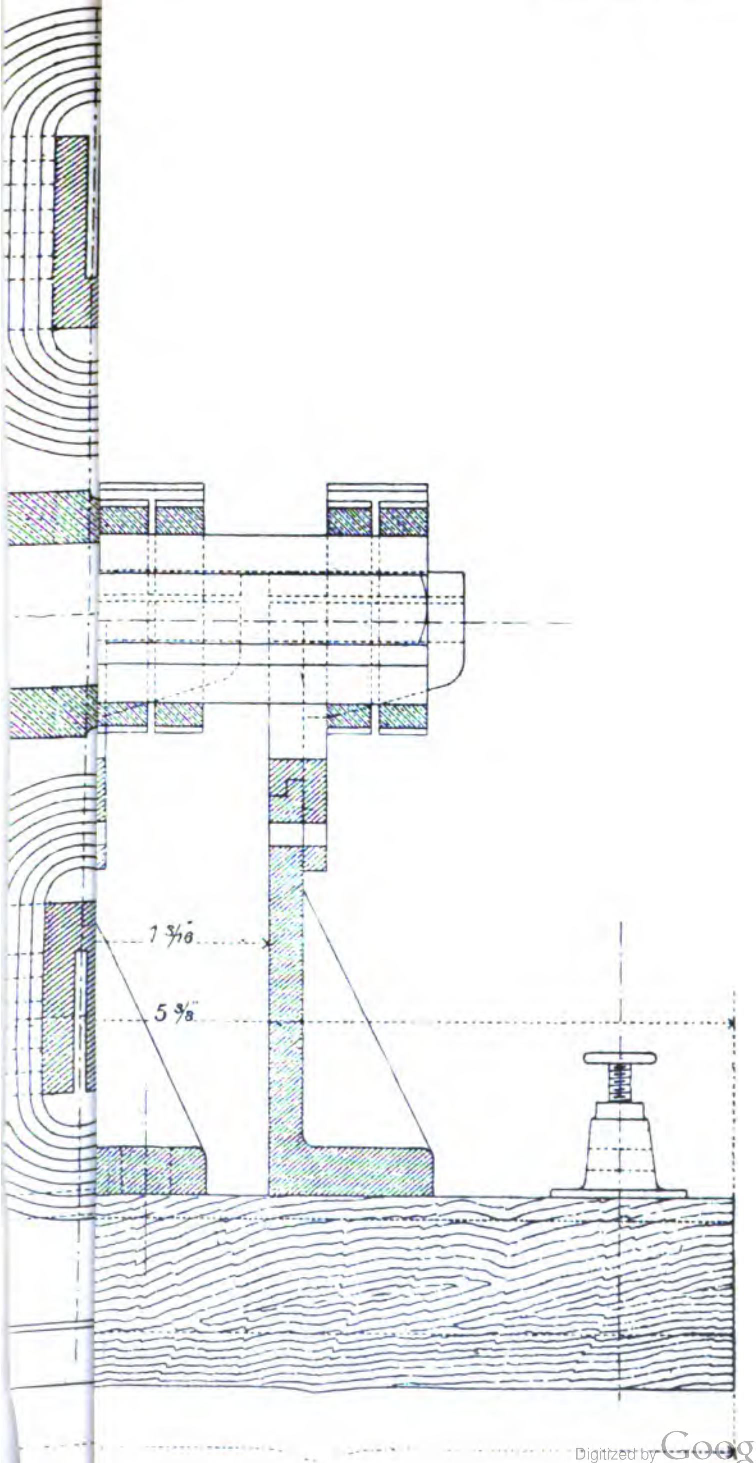
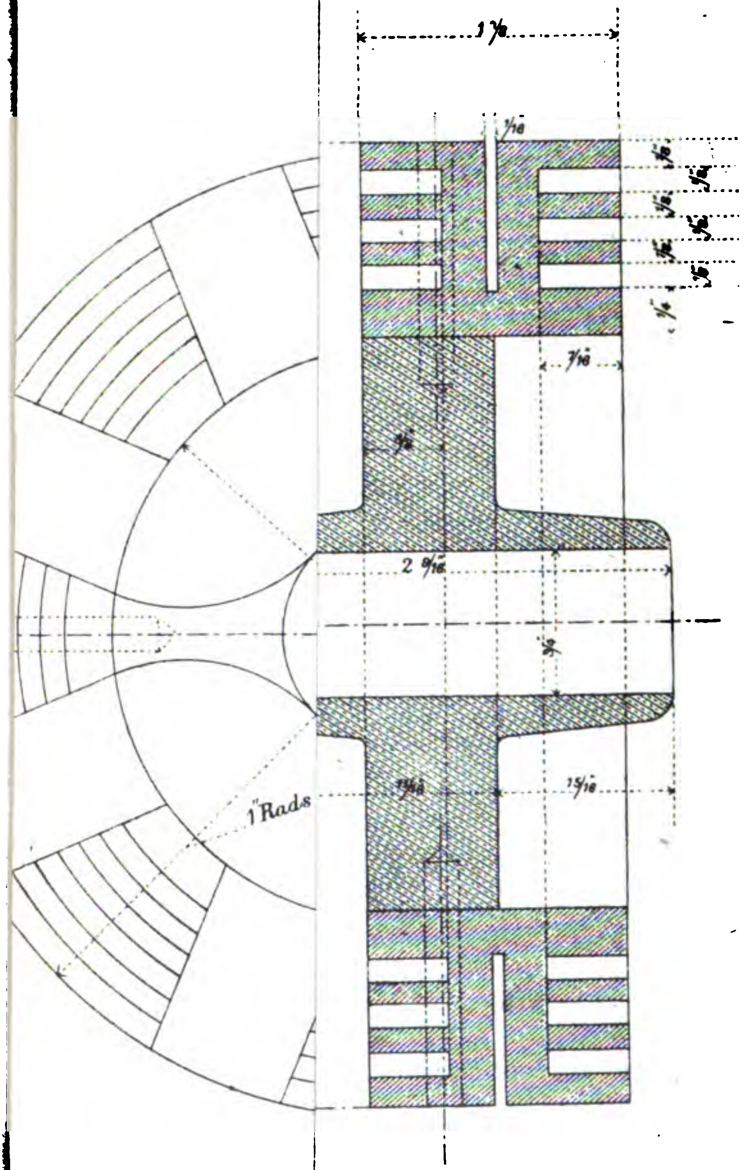


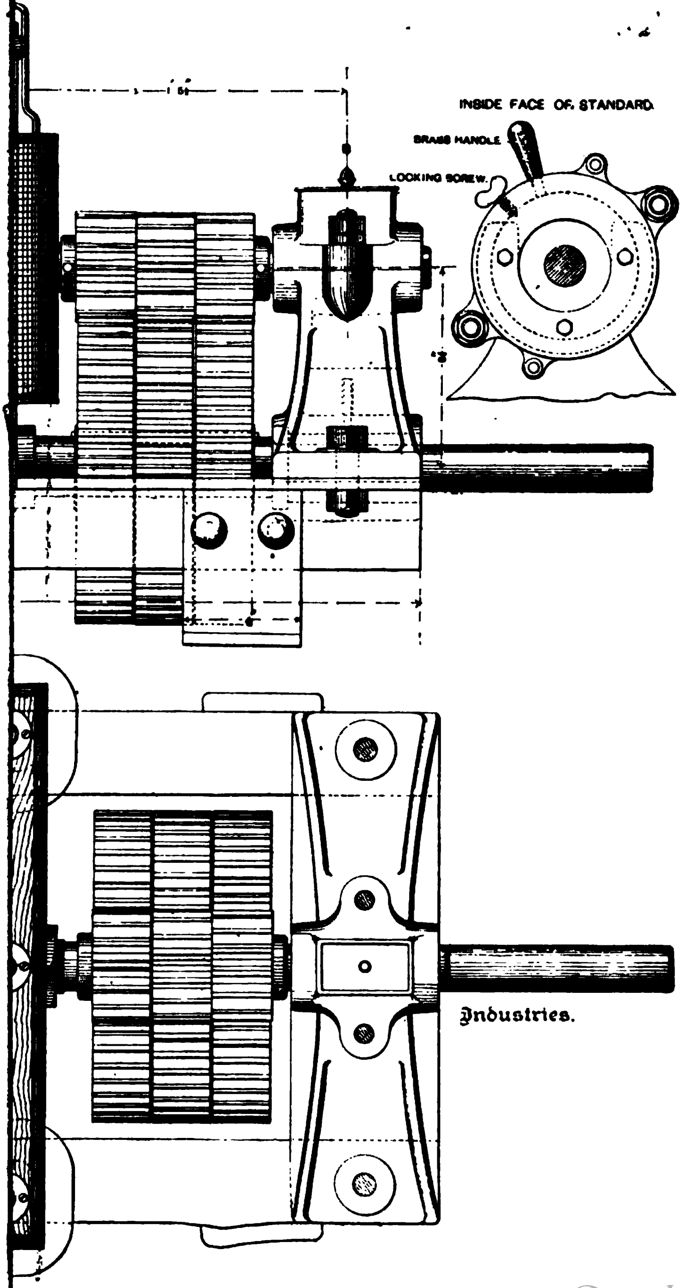
Plate xvi





R.

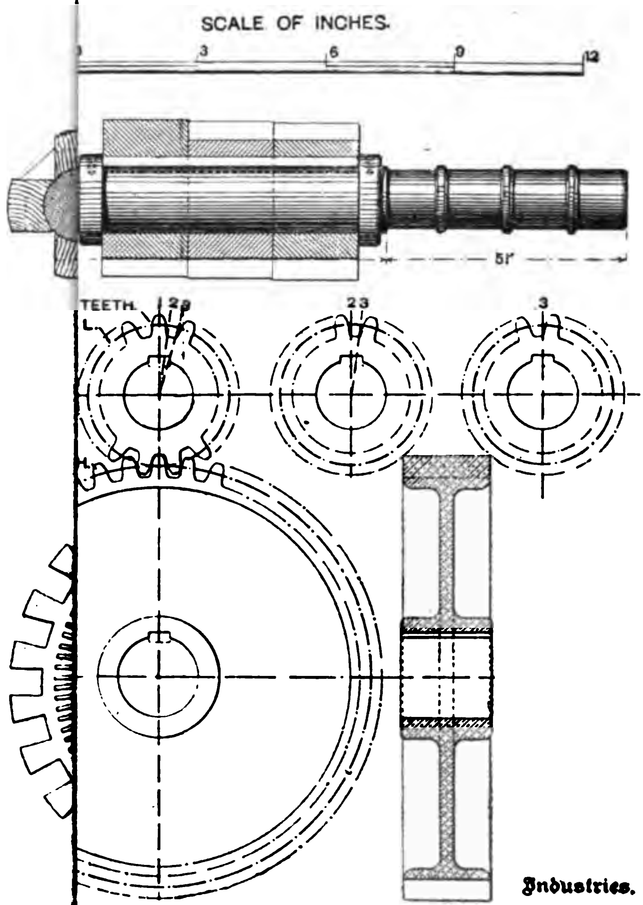
SMALL BRUSH



Industries.

Plate xix

MOTOR.



Industries.

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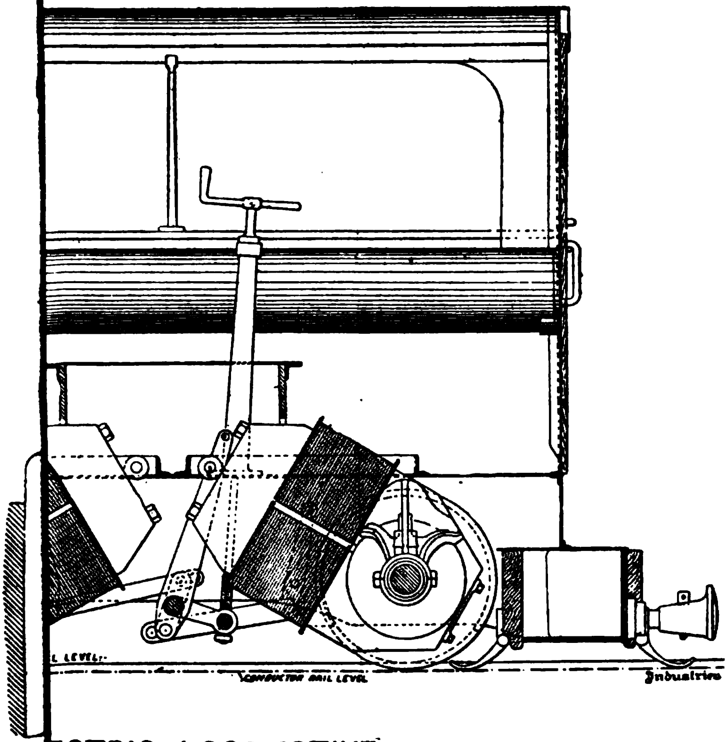
Plate xx



ECTRIC LOCOMOTIVE.

Plate xxi

RDEY ALTE

UTPUT 37½ AMF

H.P. AT 500 REV

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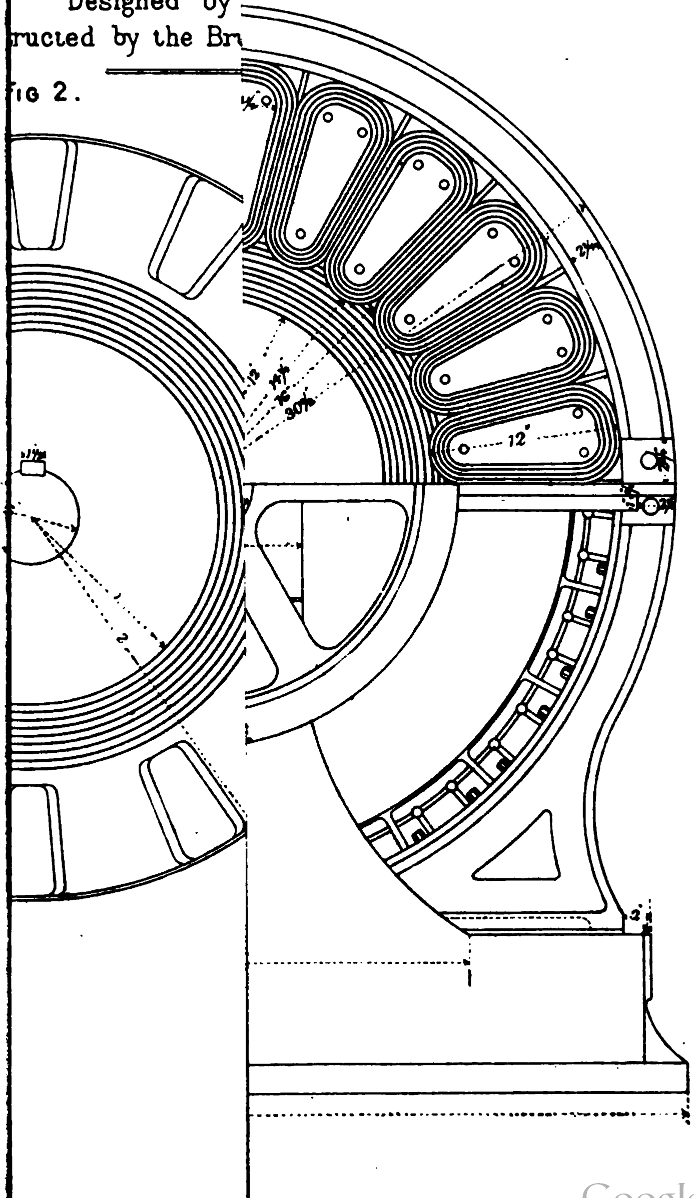

Plate xxii

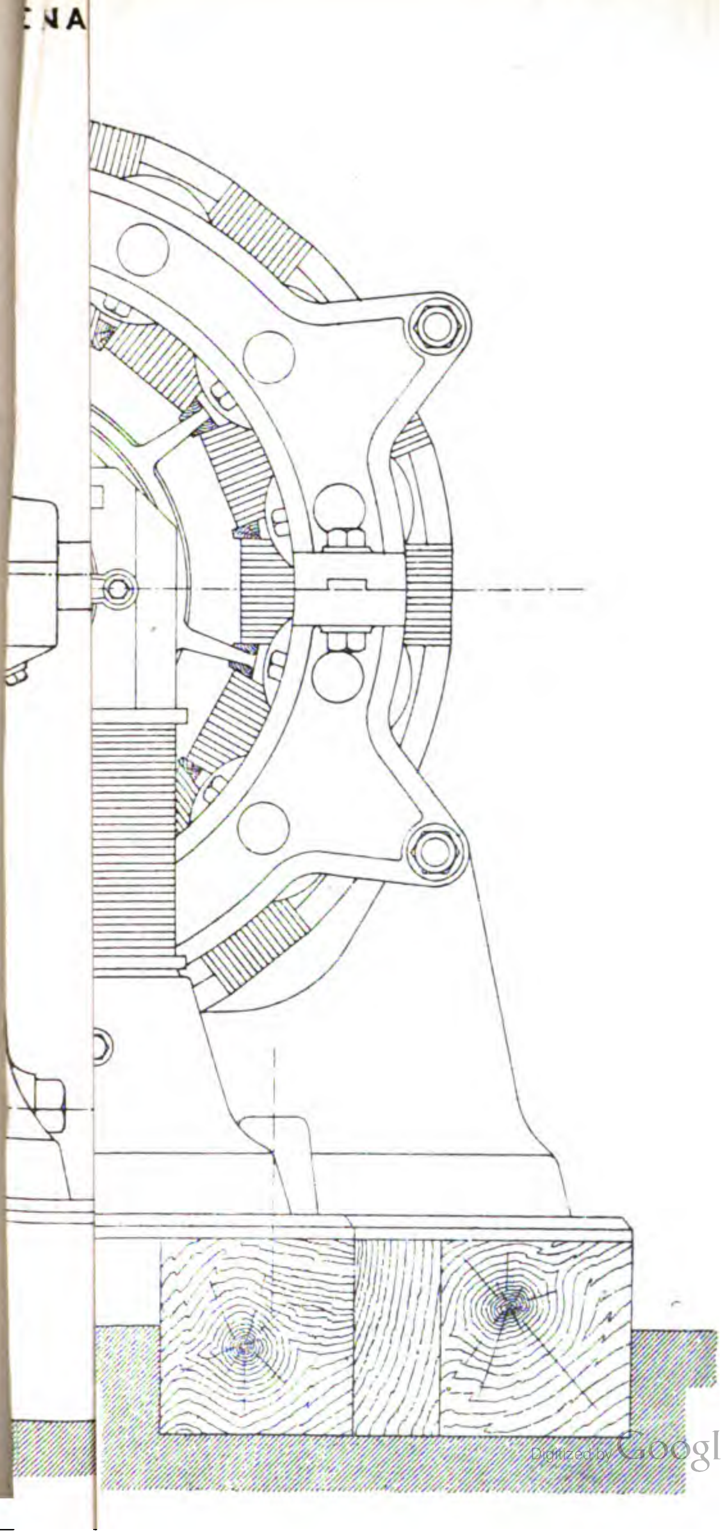

Plate xxiii

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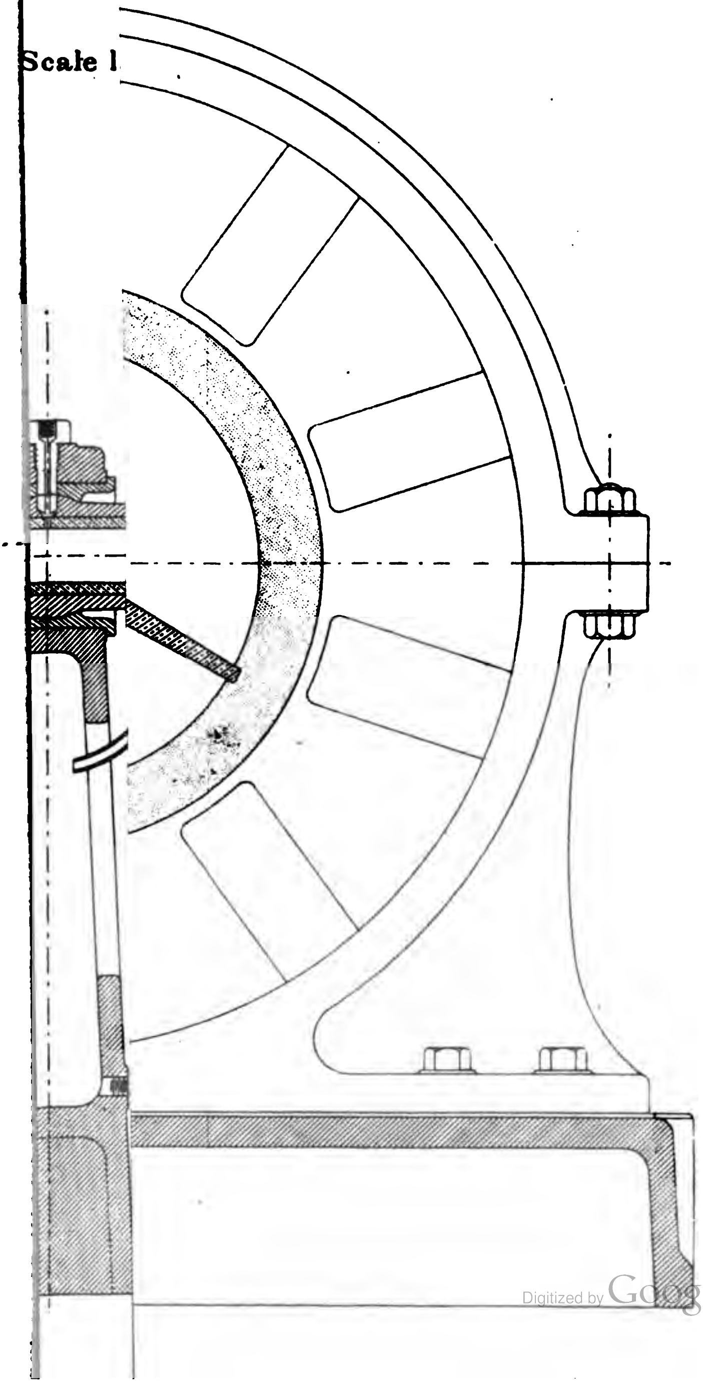

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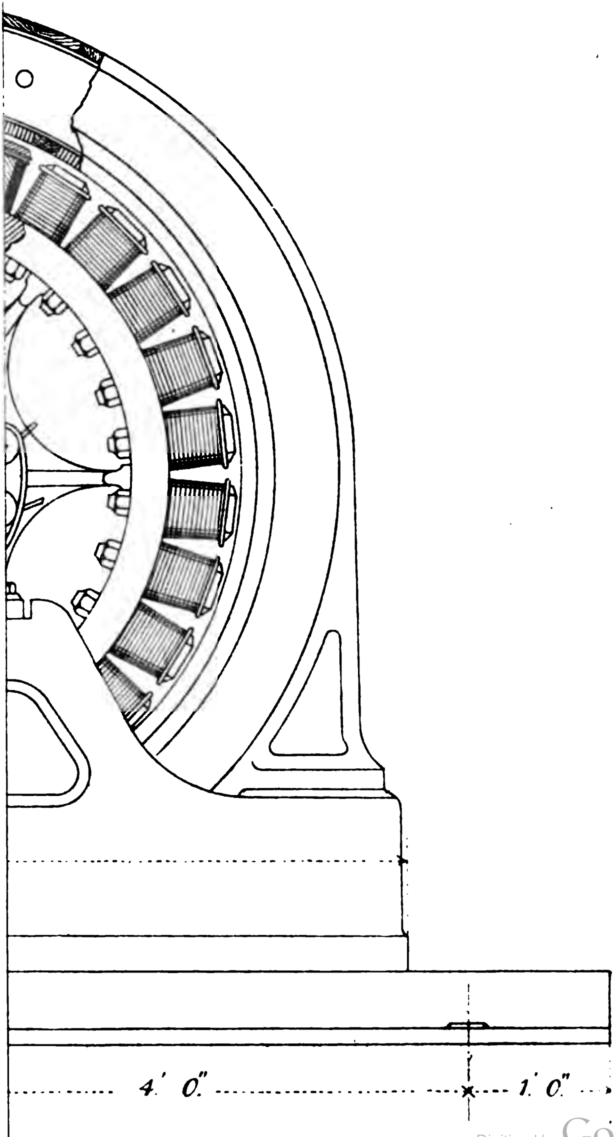
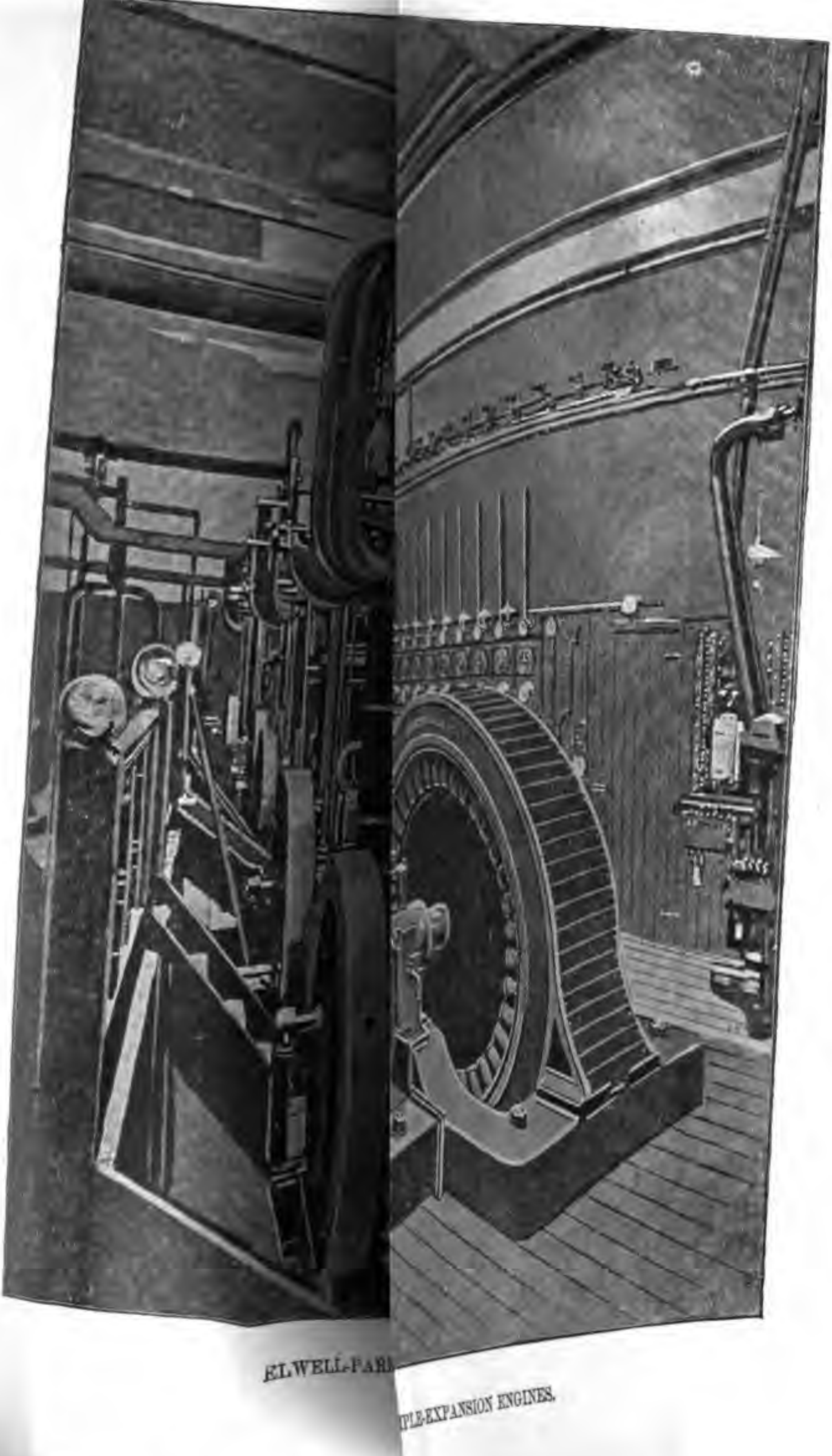
Plate xxiv

-PAR
UT 20
H.P. AT
Constru

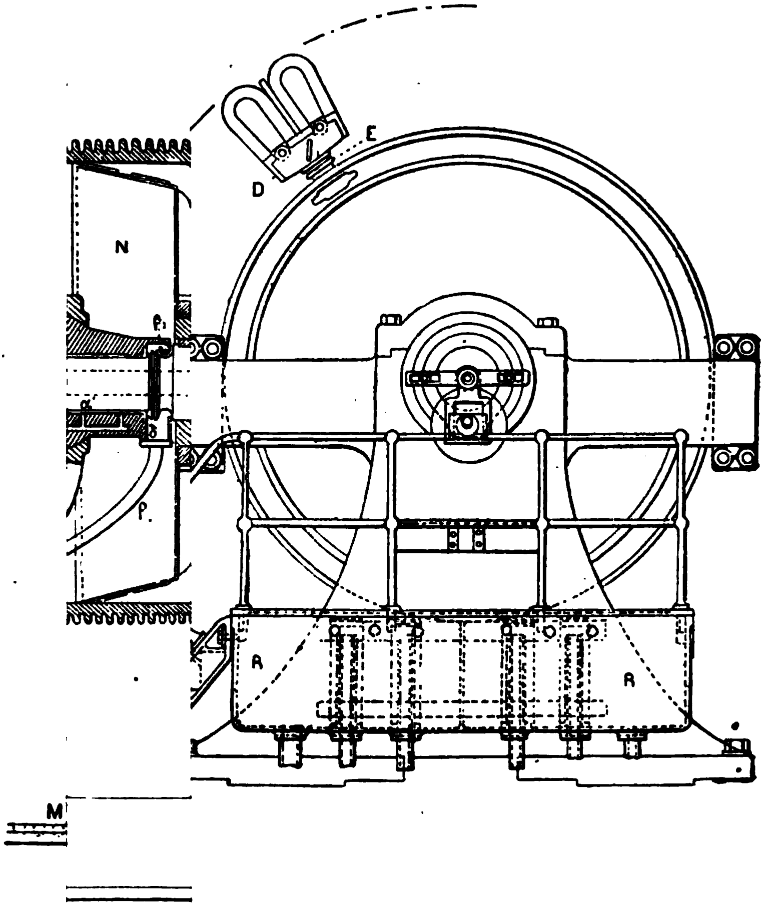




ELWELL-PARK

IPLE-EXPANSION ENGINES.

FIG. 8.



TION. 125

END ELEVATION.

ALTER

SCALE 1:50.

Plate xxvii

YNAMO.

ITI.

0 AMPERES AT 10,000 VOLTS.

FIG. 2.

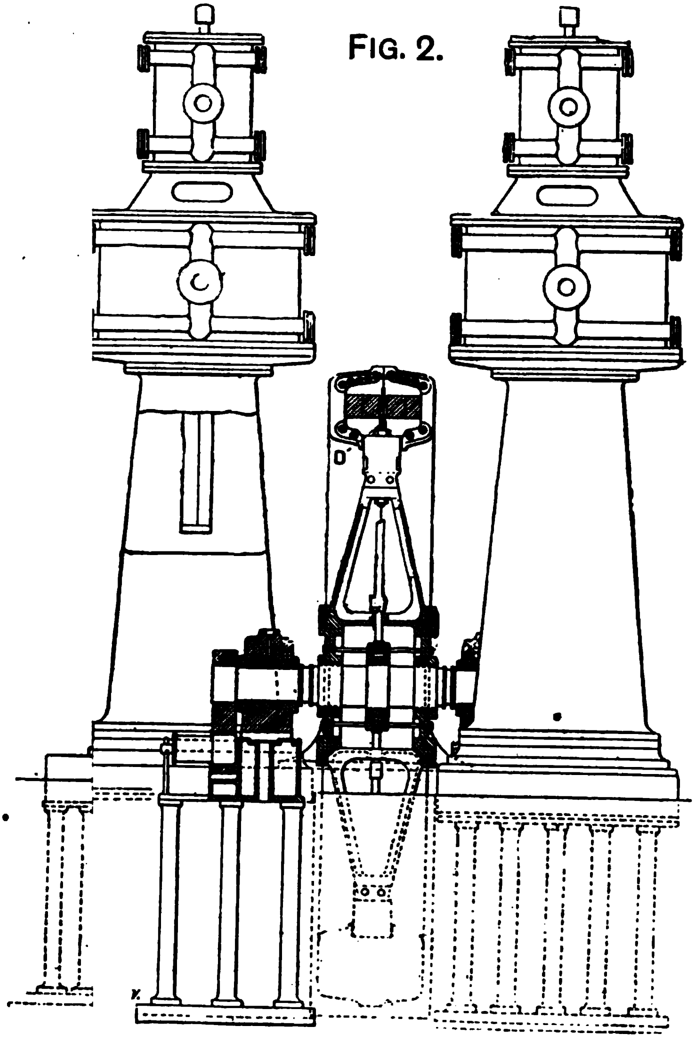


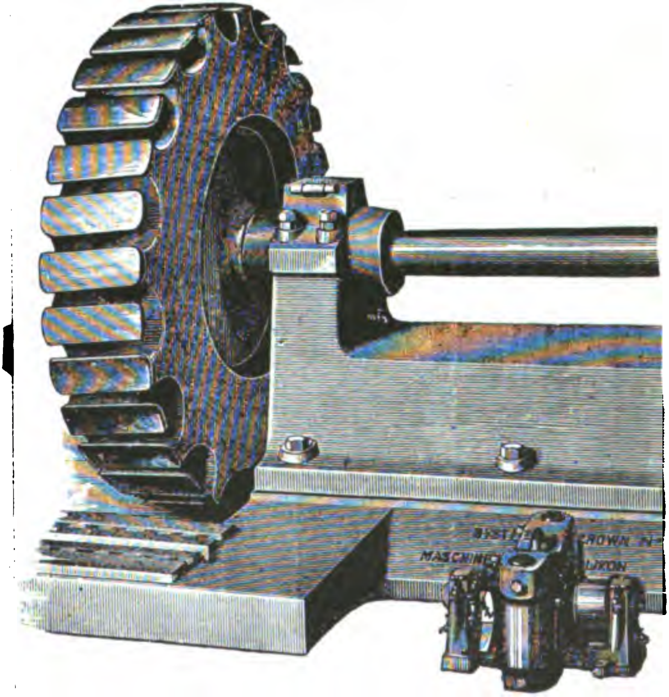
Plate xxviii

ERATOR,

NKFORT.

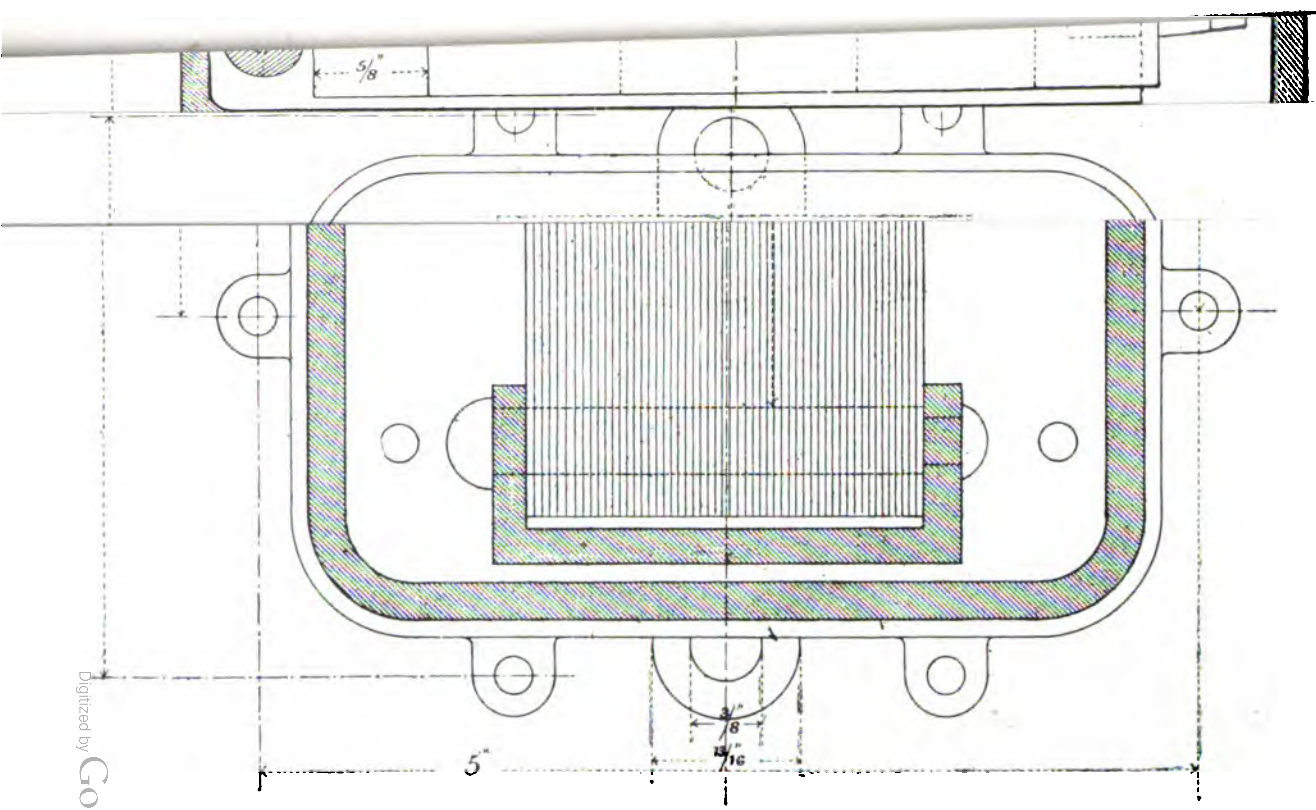
AT 150 REVS. PER MIN.

FIG. 2.



CHINE WORKS.

Plate xxix



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